Offshore wind, ready to float? Global and UK trends in the floating offshore wind market

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Preface

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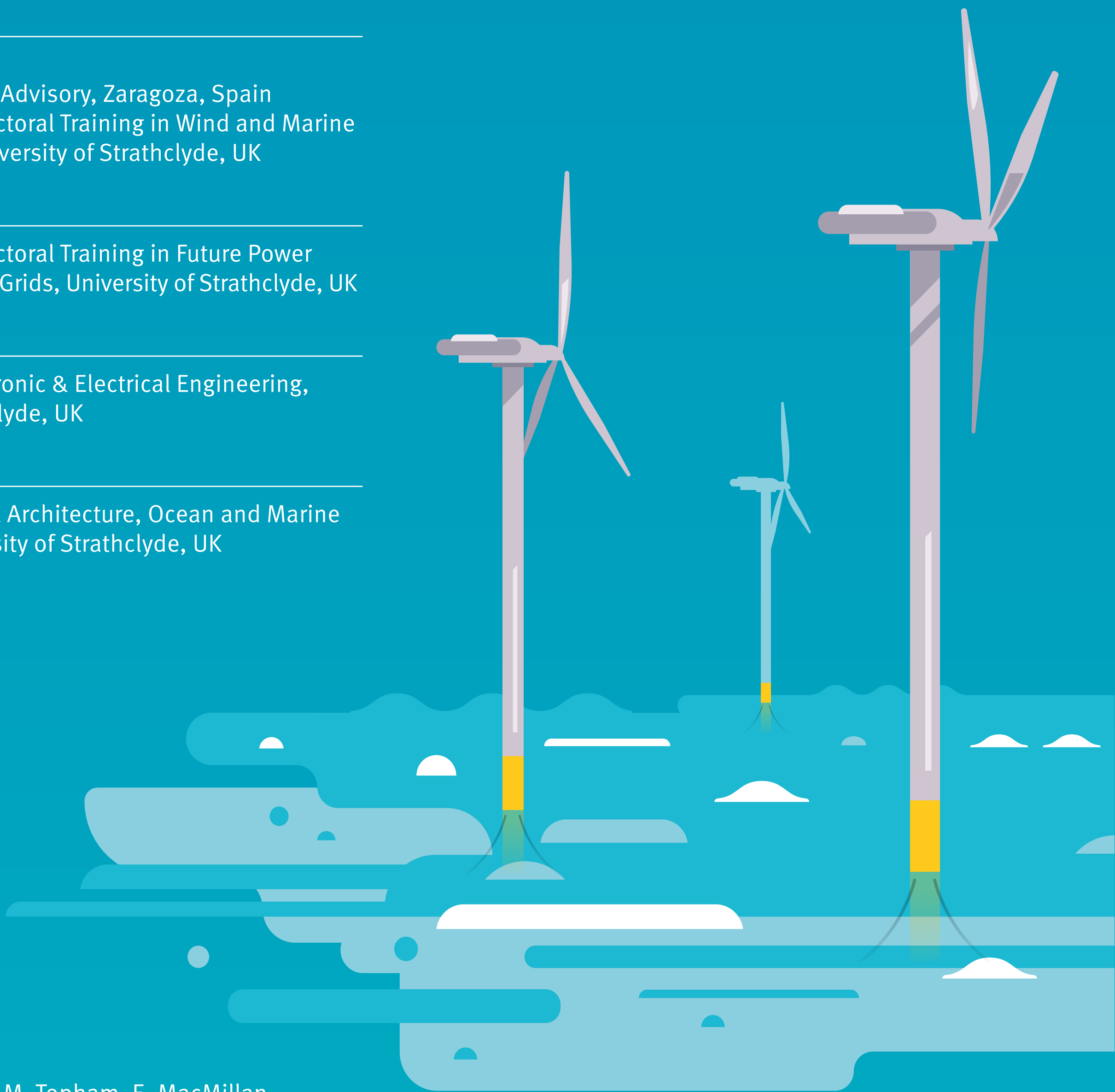

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Executive Summary

Overview and key findings

Floating wind foundations could unlock offshore wind power generation in deeper and more remote waters. This report examines how quickly floating wind is progressing towards becoming a major contributor to the global electricity supply mix. It contains a special focus on developments in the UK and Scotland, uncovering challenges that may undermine the growth of floating wind, as well as policy recommendations that could help overcome these.

A summary of the key findings is presented below:

Global focus

The floating wind market is growing steadily, expanding from almost zero installed capacity in 2008 to 57 MW in 2018. Looking forward, there is an impressive pipeline of projects for future deployment. By 2030, global capacity of floating wind could be as high as 4.3 GW.

Deployment of installed capacity has to date been dominated by the UK and Japan, and the vast majority of these foundations have been designed and developed by companies in Norway and Japan. New entrants, most notably the USA and France, are expected to challenge for leadership in both deployment and design.

Whilst SMEs have played a central role in driving growth in the sector, **multi-national companies are investing in floating wind deployment and design**. These include: (1) oil and gas majors; (2) energy utilities; and (3) Original Equipment Manufacturers (OEMs).

Floating wind rated turbine capacity more than tripled between 2008–13 and 2013–18. However, the majority of projects remain single-turbine demonstration projects, with just one array deployed.

Projects' distance from shore has doubled to average 11km but their depth has increased by just 7% between 2008–13 and 2013–18. However, at an average depth of 65m, projects are operating in waters deeper than most bottom-fixed foundations are economically capable of.

UK and Scotland focus

The UK is the world leader in floating wind deployment, with 56% of global capacity. Retaining this future lead will, however, be likely to depend on it retaining an open trading relationship with the EU, a relationship that it has depended on heavily to deliver its two existing floating wind projects. Taking opportunities to grow the UK content of the offshore wind supply chain may help to mitigate some disruption post-Brexit.

The **removal of the UK's Renewables Obligation (RO) has created a gap for long-term support** of small-scale pre-commercial floating wind projects. Domestic support will become even more important, should the UK lose access to European technology demonstration funding post-Brexit.

Introduction

Wind power generation has grown dramatically during the 21st century and is now at the forefront of the fight against climate change. Its growth has been spearheaded in recent years by the deployment of offshore wind, with installed capacity growing dramatically from 1.4 GW in 2008 to 24 GW in 2018. However, offshore wind still only accounted for 0.2% of global power generation in 2018, signalling the huge potential for offshore wind to make further inroads in the future.

Despite the sector's impressive growth, deployment of offshore wind has mostly been limited to relatively shallow water, normally less than 60 m. This is in part due to the limitations of existing turbine foundation technologies, which make deployment in deeper waters cost-prohibitive.

The inability to locate future wind farms in deeper, more remote waters is likely to constrain future growth of offshore wind, by limiting the geographical reach and thus the potential scale of deployment. Taking Scotland as an example, over 70% of its estimated offshore wind resource is located in waters deeper than (Scottish Government 2018b) 60 m. A similar situation can be found in other regions, such as off the coasts of Japan, Europe and the USA. We also find that more remote offshore locations typically offer better, more stable wind regimes. This can yield potentially superior capacity factors – essential to further reducing the levelised cost of offshore wind energy. Consequently, there is a need for technological innovations that can unlock wind power generation from deeper, more remote offshore waters.

Floating wind foundations present one possible answer. These are moored to the seabed, rather than fixed, and are categorised into three main groups: semi-submersible and barge; spar; and tension leg platform (TLP) (see Figure 1). These differ in the way that they achieve static stability, i.e. how they counteract the aerodynamic thrust acting on the wind turbine to ensure it remains in an upright position while floating.

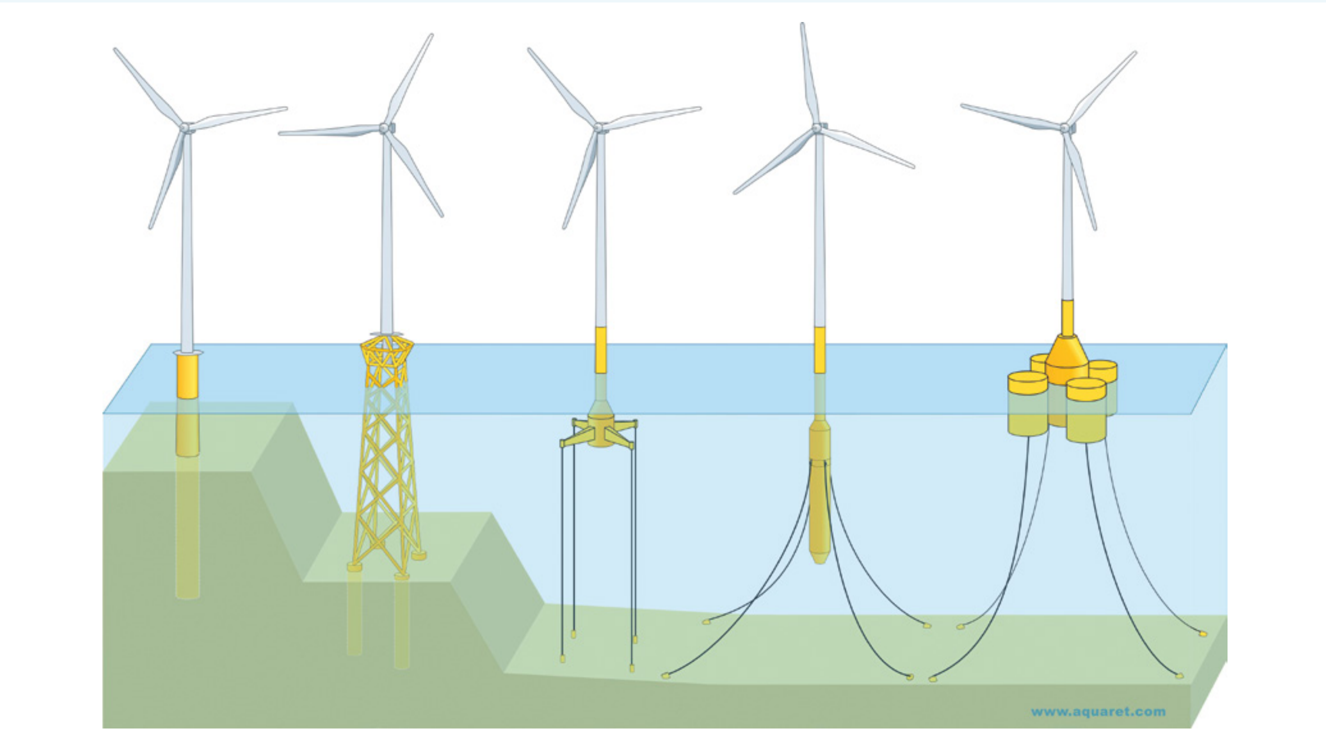

Figure 1: Common fixed and floating offshore wind structure designs (Source: www.aquaret.com).
From left to right: driven monopile; steel jacket tower; tension leg platform; spar buoy; semi-submersible

Rationale and research questions

Today relatively little is known about the state of the floating wind market, how it has evolved in recent years and, indeed, how it may evolve in the future. Consequently, we have little clarity over whether or not the market is growing, and if so where, how and why. To address these questions, this report examines the following, for both past and future market trends:

1. Number of projects and scale of installed capacity;
2. Leading countries in terms of deployment and foundation design;
3. Types of foundations being installed; and
4. Scale, depth and distance from shore of projects.

Answering these questions will help us better understand how the technology is maturing and the types of strategies that may be required to overcome potential challenges and support the sector's development in the future. Whilst the report employs a global outlook, it pays special **attention to developments in the UK and Scotland**, given their leading role in growing the floating wind sector. Against this backdrop, the report makes a series of policy recommendations to help support the sector's growth.

Methodology

The report employs a mixed-method approach. It considers both past and future market trends by examining the characteristics of **60 floating wind projects**, aggregating this data to a national and then a global level. This is complemented by **two qualitative case studies** of Scottish floating wind projects, alongside other sector-level documentary analysis relevant to the floating wind sector.

Results

Past and future growth

Floating wind technology is at an important juncture in its life cycle, on the cusp of progressing from pre-commercial demonstration to large-scale commercial deployment. The sector has enjoyed steady growth, **progressing from almost zero installed capacity in 2008 to 57 MW in 2018**, across 12 projects in six different countries.

Looking forward, we find a healthy pipeline of 268 MW of floating wind projects that have at least applied for consent – five times today's total. Another 24 projects are at a very early stage of planning (i.e. have not applied for consent) and would deliver a further 5.9 GW of installed capacity, potentially before 2030.

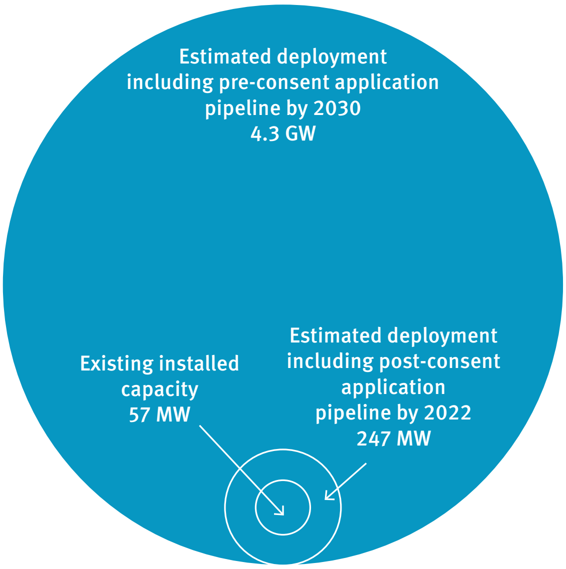

Figure 2: Estimated potential deployment of floating wind pipeline

So how much floating wind capacity could be installed by 2030? Taking the proportion of UK offshore wind projects that have historically moved from pre-consent application to commissioning, the report estimates that **4.3 GW of floating wind capacity could realistically be commissioned globally by 2030** (Figure 2). Whilst this estimate is accompanied by some important caveats (see main report), this growth trajectory is broadly in line with how quickly traditional bottom-fixed offshore wind grew at a similar stage in its life cycle.

International leaders – deployment

With 32 MW and 56% of global capacity, the UK is the current world leader in floating wind deployment. Japan is a close second with 19 MW of deployment. Considering only projects that have applied for consent, most projects would be delivered by France and the UK, but with significant capacity also deployed in Portugal, Spain, Japan and the USA (Figure 3). The **USA and the UK account for almost three quarters of capacity for very early stage projects**.

We identify a number of **new entrants moving into the floating wind market, such as Spain, France and the USA** – adding further competition to the sector. Furthermore, the countries with the strongest past and future deployment pipeline are typically those with the most attractive investment environment for offshore wind and a strong deep-water wind resource.

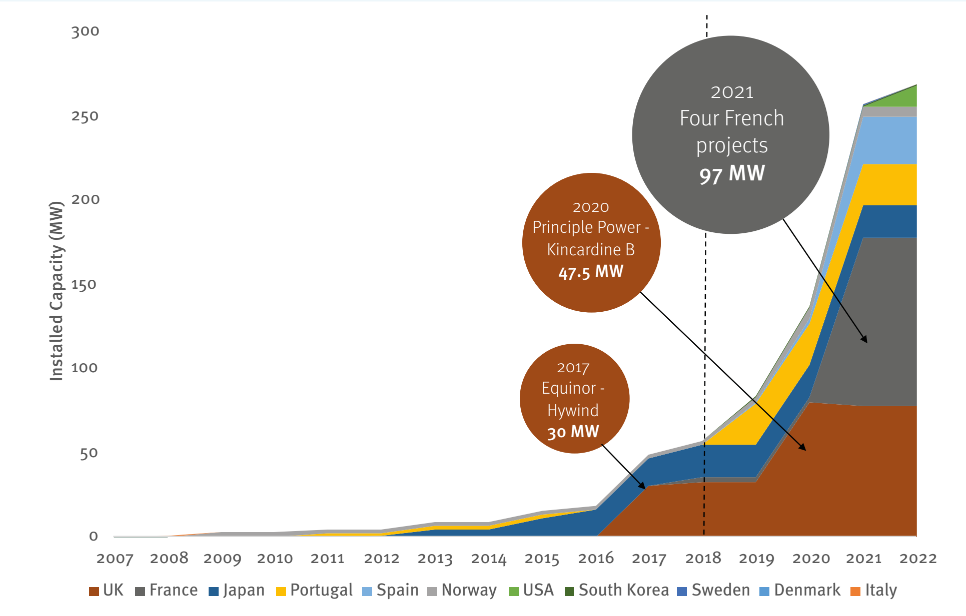

Figure 3: Cumulative installed capacity to 2022 by nationality, excluding early planning and decommissioned projects.

NOTE: Record-capacity installations shown by circle area and are sized proportionally.

International leaders – foundation design and development

Norwegian foundation designers account for 57% of current installed capacity, with Japan a relatively close second. Norway's clear lead is really accounted for by a single project – the 30 MW Hywind Buchan Deep in Scotland. However, **looking forward the USA is expected to dominate** with 41% of capacity that has applied for consent, largely driven by Principle Power's semi-submersible concept. France ranks second (21%) and Norway third (12%). The USA also leads the pre-consent application pipeline but faces stiff competition from France, which would account for a similar share – together they would make up almost three quarters of all capacity.

Key actors

We find that, whilst SMEs play a central role in driving growth in the sector (e.g. Principle Power), **multi-national energy firms are also playing a key role**. These include oil and gas majors (e.g. Equinor), energy utilities (e.g. Iberdrola) and OEMs (e.g. Siemens Gamesa), which have engaged strongly in both floating foundation design and project development. Leveraging these companies' financial and political capital will certainly support market growth. However, it also creates a pressure on floating wind technology to deliver utility-scale power generation within a relatively short timescale. Public sector support for full-scale demonstration will therefore be critical to reducing the pressure for floating wind to be deployed prematurely on a commercial basis, which could result in catastrophic technical failures and harm its perceived legitimacy.

Technological trends – foundation design

Today spar floaters dominate, accounting for two thirds of installed capacity, primarily from Equinor's Hywind. In the medium term, a diversification of foundation types is expected, given how each design has its own advantages and disadvantages in relation to any given project's individual characteristics. However, **looking further forward, semi-submersible foundations are expected to dominate the market**, accounting for almost all capacity of projects at an early stage of planning. This trend disguises the fact that **a sizeable proportion of these semi-submersible projects have significant design variations around**: (1) situating multiple turbines on single foundations; (2) alternative turbine types (e.g. kite, vertical axis); and (3) co-locating wind with other forms of renewable generation (e.g. wave, solar). This would make for a substantially more heterogeneous marketplace in the future.

Technological trends – scale, depth and distance

To gauge the maturity of floating wind, we examined how the technology has 'scaled up'. We find that **turbine capacity has more than tripled and turbine hub height has almost doubled** between 2008–13 and 2013–18. However, less progress has been made in terms of the number of foundations per project, with the **majority still being single-turbine demonstration projects**. Looking forward, numerous multi-foundation arrays with turbines >5 MW are being planned, with three 8 MW turbines already being installed off Portugal. Early stage planned projects are regularly over 200 MW.

Table 1: Comparison of project technical characteristics between 2008–13 and 2013–18

Measure	Six year average (2008-13)	Six year average (2013-18)	Change
Turbine capacity (MW)	0.75 (n=14)	2.34 (n=13)	+212%
Turbine hub height (m)	33 (n=11)	63 (n=10)	+91%
Number of foundations	1 (n=14)	1.4 (n=13)	+40%
Depth (m)	61 (n=13)	65 (n=11)	+7%
Distance (km)	5 (n=13)	11 (n=11)	+120%

Over the same period, the average **distance from shore has doubled to 11 km but average depth has seen only a 7% increase to 65 m**. Importantly, however, projects are already typically **operating in waters deeper than those which most bottom-fixed foundations are economically capable of operating in** (i.e. greater than 60 m), thus already adding value. It is unclear why increases in depth have been less dramatic, but factors responsible may include technological limitations, attempts to mitigate technical risk or developers taking advantage of shallower sites first. There are a significant number of highly ambitious early stage projects that would be located in very deep and remote waters – **regularly deeper than 250 m and 25 km offshore by the 2030s**.

Special focus: UK and Scotland

The UK, and more specifically Scotland, are world leaders in deployment of floating wind. This trend could well continue, with another 78 MW of projects that have at least applied for consent, in addition to a further 1.9 GW of projects that have yet to do so. So what challenges could undermine these ambitions and what steps can be taken to drive growth?

Supply chain

Despite this impressive progress, the UK is the only country with highly ambitious plans for floating wind deployment but no major floating foundation designers. In a similar situation to the traditional bottom-fixed offshore wind supply chain, we find that UK firms were mostly involved in project development and O&M, but much less involved in capital expenditure, such as turbines, foundations, etc. The UK's two existing projects clearly point to how **the UK is very reliant on overseas products and services to deliver its floating wind projects**, with almost two thirds of the companies directly involved non-UK headquartered. It therefore **remains unclear whether floating wind presents a clear opportunity for the UK to grow its share of content of the offshore wind supply chain**.

The overwhelming majority of these overseas firms are either from the EU or the European Economic Area – and by extension the European single market. **Brexit therefore raises serious questions about how leaving the single market and the customs union could impact negatively on the prospects of future UK floating wind projects**. This is due to the potential introduction of tariffs, supply-chain disruption and a lack of access to skilled labour. It also raises concerns about the health of the UK firms involved in floating wind, which currently export products or services to EU countries. A weakening of these firms may erode the UK's capacity to deliver its current pipeline of floating wind projects.

Innovation support

A lack of pre-commercial revenue payments and an over-reliance on fragile EU innovation support are expected to undermine growth of floating wind in the UK. Both of the UK's floating wind projects that have been delivered to date have relied on the Renewables Obligation (RO). This has, however, now been discontinued, with no analogous scheme replacing it (Figure 4). Instead, floating wind developers are left with the Contracts for Difference (CFD) as the only significant route to long-term subsidy. However, relatively small-scale floating wind projects are expected to struggle to compete with much cheaper forms of power for subsidy (e.g. bottom-fixed offshore wind).

Most other funding available to UK floating wind projects is via the EU (e.g. Horizon 2020, EU Innovation Fund, etc). As such, Brexit could threaten the UK floating wind sector by preventing UK-based developers from accessing the wealth of EU energy innovation funding, with no guarantee that they would be replaced like-with-like by funding from UK government or devolved administrations.

Should the UK fail to replace the RO with a similar mechanism and/or retain access to EU innovation funds, UK floating wind projects are unlikely to be able to source the patient pre-commercial capital they require to drive costs down. In the absence of such subsidy, servicing niche markets that have above-average electricity costs (e.g. wind-to-gas, off-grid islands) is likely to offer an important path for future floating wind projects and to drive down costs through economies of scale.

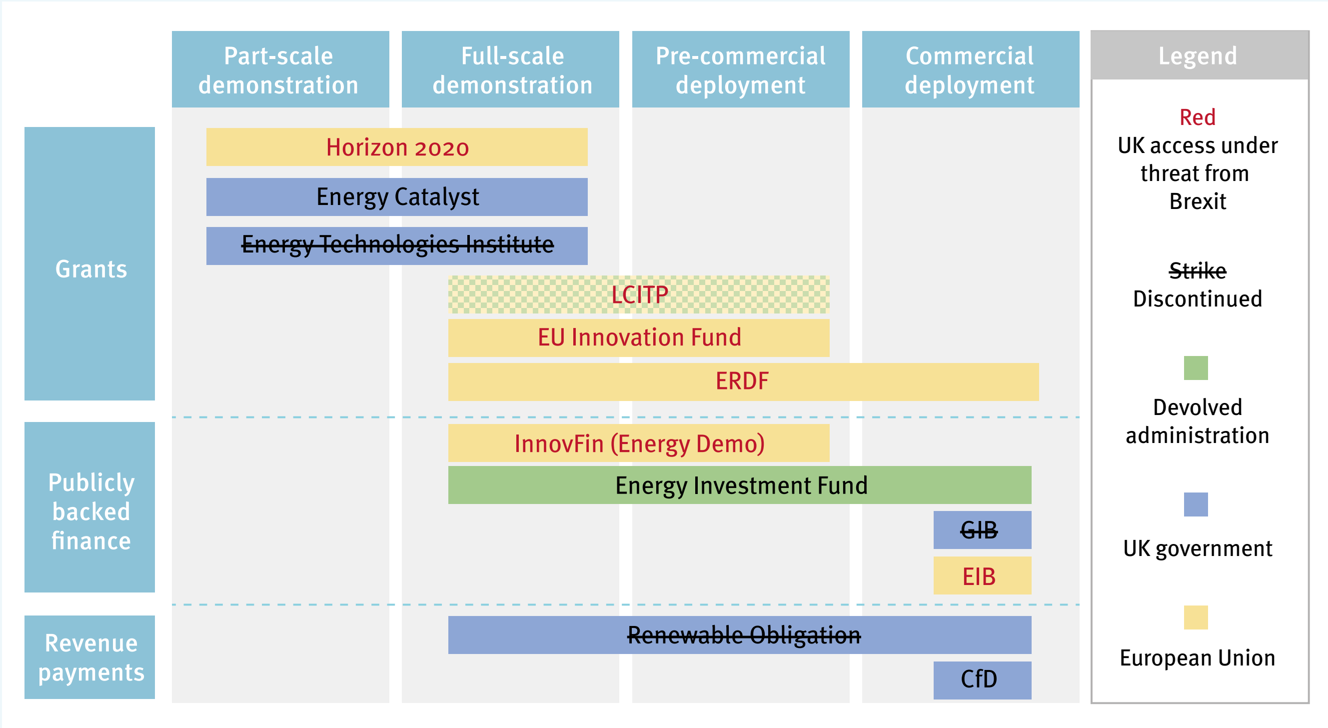

Figure 4: Major funding programmes offering innovation support to floating wind projects in the UK

NOTE: LCITP - Low Carbon Infrastructure Transition Programme; ERDF - European Regional Development Fund; GIB - Green Investment Bank; EIB - European Investment Bank; CfD - Contracts for Difference

UK and Scotland policy recommendations

Drawing on our findings, we present five policy recommendations for the UK and devolved governments:

1. **EU innovation support** – Move to retain access to EU demonstration funding post-Brexit. If unsuccessful, the UK must consider how it can use its own public funds to cover any shortfall, with a focus on both grants and government-backed finance for demonstration schemes.

2. **Long-term pre-commercial subsidy** – With the RO now discontinued, there is no longer an appropriate, long-term subsidy to support pre-commercial floating wind projects. One option would be to create an innovation-oriented CfD pot that allows for more expensive pre-commercial technologies (e.g. floating wind, tidal stream) to compete against one another for a guaranteed strike-price.

3. **Niche markets** – Fund research to identify potential niche markets in the UK for floating wind (e.g. oil and gas extraction, island consumption), the associated cost benefits and barriers to deployment. Findings would inform what additional support is required for developers to access these markets, to act as a springboard to wide-scale deployment.

4. **Grow UK supply chain content** – Help support UK firms to identify and take advantage of new supply-chain opportunities unique to floating wind. In parallel, help firms already part of the traditional offshore wind supply chain, and those from other sectors with overlapping capabilities, to transition into the floating wind sector.

5. **Minimise supply chain disruption** – Consider how withdrawing from the EU will impact on the cost and delivery timeline of floating wind projects in both the UK and Europe, as well as the financial performance of UK offshore wind companies from both a domestic and an export market perspective. In turn, consideration should be given to what trading arrangements (e.g. tariffs) will support the future growth of floating wind in the UK and Europe more widely.

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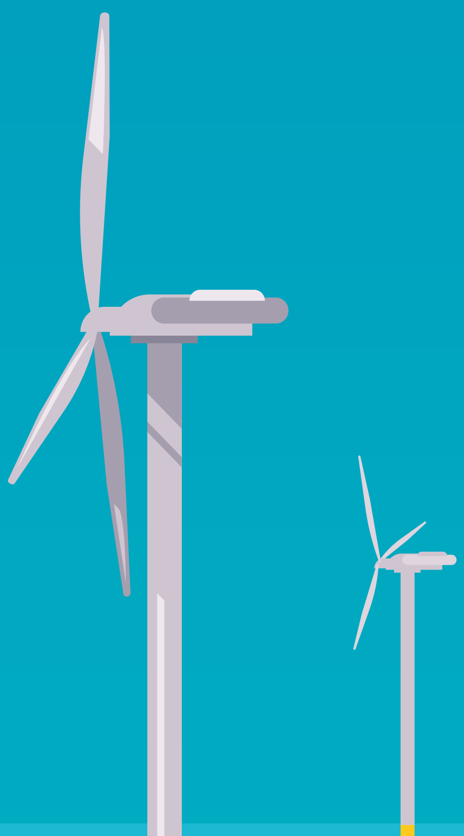
Introduction



Wind power is at the forefront of the fight against climate change and decarbonising the energy system. The wind sector has grown dramatically during the 21st century, spearheaded in recent years by an impressive growth in offshore wind capacity, with installed capacity growing from 1.4 GW in 2008 to 24 GW in 2018 (IRENA, 2019a).

A dramatic reduction in the cost of producing energy through offshore wind capacity has been both a cause and effect of this growth, with the average levelised cost of energy (LCOE) having fallen by 20% between 2010 and 2018 from $159/MWh to $127/MWh (2018 prices)(IRENA, 2019b). Costs have fallen due to a wide range of factors, including: (1) technological, installation and logistical innovation; (2) economies of scale in operation and maintenance (O&M) (e.g. larger turbines); and (3) improved capacity from higher hub heights, better wind resources from deeper waters and larger rotor diameters (IRENA, 2019b).

The latter is in part associated with offshore wind projects moving into deeper, more remote waters. Recent projects have been installed at depths typically of between 10 and 55 m and distances of up to 90 km offshore, compared to depths of 10 m and distances of 20 km between 2001 and 2006 (IRENA, 2019b). This trend is being driven by an appetite for locating wind generation in areas 'with better, more stable wind regimes' (IRENA, 2019b p.23), the aim being to improve projects' capacity factors and, more broadly, to capture the huge potential resource of deep waters. For example, looking out to 50 nautical miles from the US coastline, 59% of the potential offshore wind resource in the USA (2,450 GW) is estimated to be at depths of 60 m or (NREL 2010) more.[1] Significant deep-water wind resource has also been identified in Europe (EWEA, 2013) and Japan (Govindji, James and Carvallo, 2014), the latter with 80% of its potential wind resource in water greater than 50m deep (MIC LLC, 2013).

To date, the additional cost of locating bottom-fixed foundations in deeper, more remote waters has largely been offset by the benefits of larger turbines accessing superior wind resources (IRENA, 2019b). However, monopile foundations, which accounted for an 75% market share of all sub-structures installed in Europe by the end of 2018 (Wind Europe, 2019), are generally considered cost-effective only in water depths of up to 50 m (Carbon Trust, 2015). Other bottom-fixed foundation designs, such as jackets, can offer cost-effective installation in deeper waters. However, new turbine foundation designs will be required to unlock wind resources in very deep waters (approximately 60 m plus). There is also a concern that the growing popularity of offshore wind in some countries is diminishing the availability of sites in cost-effective, near-shore, shallow-water locations. Consequently, there is a growing need for innovative turbine foundation technology that can unlock wind power generation from deeper, more remote offshore waters. Floating wind foundations seek to address this challenge.

This report presents a global analysis of recent market and technology trends in the floating wind energy industry to provide a clearer picture of the sector's level of maturity and growth trajectory. Considering both past and future trends, we examine the:

1. number of projects and scale of installed capacity;
2. countries leading in terms of deployment and foundation design;
3. types of foundations being installed; and
4. scale, depth and distance from shore of projects.

In the context of these results, we consider future challenges and wider implications for the global floating wind sector.

1 'This estimate assumes that one 5-MW wind turbine could be placed on every square kilometre of water with an annual average wind speed above 7.0 meters per second (m/s)...Does not currently account for a range of siting restrictions and public concerns.' (NREL, 2010 p.4)

1.1 Special focus – UK and Scotland

The briefing employs a global outlook, but pays special attention to the UK and Scotland, given their leading role in growing the floating wind sector. At the UK level, investment in floating wind innovation is a strategic priority within both the Clean Growth Strategy (BEIS, 2017) and the Industrial Strategy Offshore Wind Sector Deal (BEIS, 2019b). This is because of the contribution floating wind technology could make not only to carbon emissions reduction targets but also to the UK economy. Scottish Government analysis highlights how '123 GW of the estimated 169 GW offshore wind potential in Scottish water is located in water depths exceeding 60m in Scotland' (Scottish Government, 2018b p.13).

Assuming deployment of 20 GW of floating wind by 2050, and appropriate early-stage strategic investment in UK ports and fabrication yards, the floating wind sector could yield 17,000 UK jobs and £2bn of Gross Value Added (GVA) per annum from a combination of domestic and export markets (ORE Catapult, 2018).

1.2 Report structure

The report is structured as follows:

- Section 2 offers an overview of the characteristics, advantages and weaknesses of different floating wind designs.
- Section 3 outlines the research's methodology.
- Section 4 presents the results of the analysis of which countries lead in terms of floating wind deployment and foundation design.
- Section 5 examines technological trends, including the foundation type, technical design parameters and geographical aspects of floating wind projects.
- Section 6 discusses the implications of these sectoral and technological trends at a global level.
- Section 7 considers opportunities for future research.
- Section 8 identifies challenges specific to the UK and presents policy recommendations to overcome these.
- Section 9 presents the report's conclusions.

2

Characteristics, advantages and weaknesses of floating wind

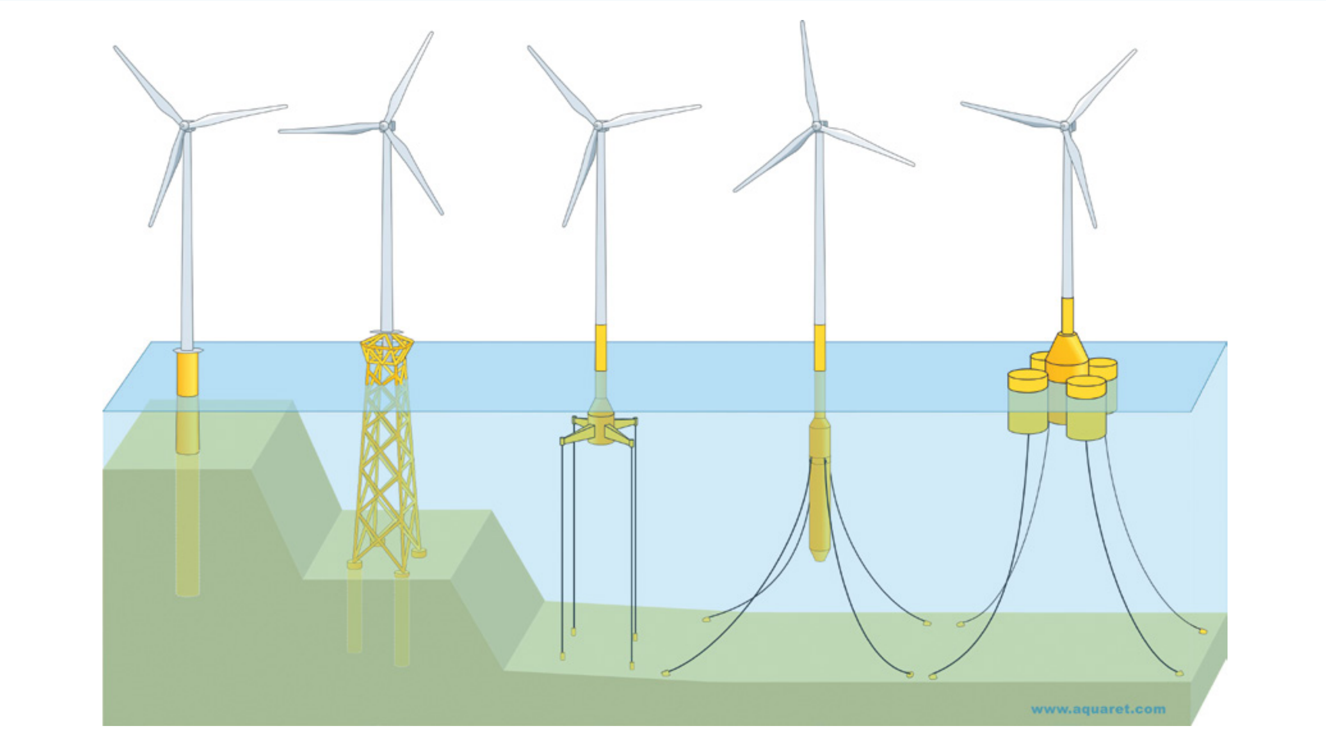


Figure 1: Common fixed and floating offshore wind structure designs (Source: www.aquaret.com).
From left to right: driven monopile; steel jacket tower; tension leg platform; spar buoy; semi-submersible

Monopile foundations – cylindrical steel tubes piled into the seabed – dominate the offshore wind market today (Figure 1) (Wind Europe, 2018). Monopile technology has the advantage of being adaptable to a wide range of seabed conditions (clay, sand, gravel, bedrock etc.)(Fulop, 2015). Monopiles are typically considered most cost-effective at up to 35 m water depth versus other foundation designs, and are thus rarely used at depths greater than 50 m (ESRU, 2015). Typically, jacket foundations, which are steel lattice structures (Figure 1) similar to those used for the foundations of offshore oil and gas rigs, are preferred in deeper waters for economic reasons. For instance, the deepest installation known to the authors at the time of writing is the 84 turbine 588 MW Beatrice wind farm off the Scottish coast, which utilises jacket foundations at a depth of up to 56 m (Utility Week, 2019).

For both monopile and jacket foundations, there is evidence to suggest that the cost of fixed-bottom wind turbines becomes less economically viable as water depth exceeds approximately 50 m (EWEA, 2013; Rasmussen et al., 2014). To enable cost-effective generation in deeper waters, there is a need for innovative foundation designs, such as floating foundations.

2.1 A typology of floating wind designs

The main difference between floating and conventional fixed foundations is that floating foundations are moored, rather than fixed, to the seabed. The characteristics and design variations of floating wind (Figure 1) can be considered in three main groups: semi-submersible and barge; spar; and tension leg platform (TLP).

The criterion usually chosen to classify the different floating wind turbine configurations is the methodology adopted to achieve static stability. The aerodynamic thrust acting on the wind turbine tends to incline the whole platform, and the platform needs to generate a moment which counteracts this effect. How this counteracting or, in technical terms, 'restoring' moment is created is what differentiates the different platform types (Figure 2).

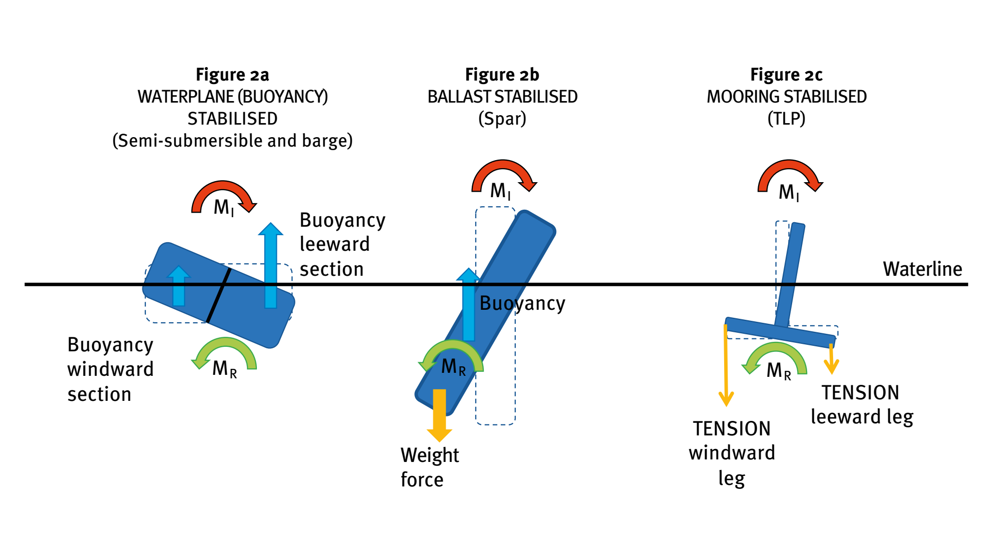


Figure 2: The three basic approaches adopted in floating wind turbines to counteract the wind inclining moment (MI = wind inclining moment, MR = restoring moment)

2.1.1 Semi-submersible and barge

Both semi-submersible and barge designs achieve the necessary static stability mainly by exploiting the buoyancy force (Figure 2a): very simply put, when the platform is inclined, the leeward part of the platform has a larger submerged volume, and the windward a smaller submerged volume, with respect to the situation at equilibrium. This means that the leeward part experiences a larger buoyancy force. This creates the restoring moment (MR) necessary to counteract the wind inclining moment (MI). In order to achieve this effect, the waterplane area[2] needs to be large and/or sufficiently spread.[3] These designs are therefore called waterplane-stabilised structures. Since they rely mainly on the waterplane area effect, the draft[4] can be shallow. While a barge configuration usually achieves this through one large waterplane area, in the semi-submersible configuration, there are a number of columns connected by bracings, producing a number of smaller areas far from the inclination axis (sufficiently spread).

To prevent the platform from drifting away due to the action of wind, wave, and marine current forces), mooring lines keep the system in place. These are typically three or six catenary[5] lines (Butterfield et al., 2007). The construction can be undertaken or assembled onshore or in a dry dock. However, the modular design implies welding joints that complicate the fabrication process and have a shape that requires a lot of space, thus narrowing down the choice of suitable port facilities (IRENA, 2016).

Semi-submersible and barge configurations are relatively easy to install, as no specialised vessels are necessary since vessels are needed for towing only. They also have an excellent adaptability to a wide range of seabed geologies (Carbon Trust, 2015), implying a low site dependency.

The main innovation priorities are: (1) reducing the weight of the platform, in order to lower costs; and (2) improving the station-keeping response of the platform, given that current mooring systems can allow a lateral motion of up to 50 m (Carbon Trust, 2015). The lateral movement presents potential problems for the export cable. In general, barges and semi-submersible platforms, as well as the other floating wind turbine configurations that adopt a catenary mooring system, are characterised by larger oscillation when subject to wave loads. This is especially true when compared to TLP. An active ballast system can be used to counteract the average inclining moment caused by the aerodynamic thrust (Carbon Trust, 2015).

2 The waterplane area is defined as the area of the section of the body at waterline level (i.e. the section of the body 'cut' by the waterline).

3 Technically, 'spread and/or sufficiently spread' means that the second moment of the waterplane area with respect to the axis of inclination should be sufficiently spread.

4 The draft is the vertical distance between the waterline and the lowermost point of the hull, i.e. how much of the structure is in the water.

5 Catenary mooring systems are commonly used with spar and semi-submersible systems, and taut-let systems with TLP. The three most common mooring-line types are as follows (Carbon Trust, 2015 p.20):
- **Taut leg** – 'synthetic fibres or wire which use the buoyancy of the floater and firm anchor to the seabed to maintain high tension for floater stability'.
- **Catenary** – 'long steel chains and/or wires whose weight and curved shape holds the floating platform in place'.
- **Semi-taut** – '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'.

Notable designs include the Windfloat design by the US firm Principle Power (Figure 3), with one turbine operational since 2018 at Kincardine off the east coast of Scotland and another installed with a 2 MW turbine in Aguçadoura, Portugal in 2011. Three Japanese designs have already been deployed at Fukushima, Japan, including: Mitsui's Mirai with a 2 MW turbine (2013) and Mitsubishi's Shimpuu with a 7 MW turbine (2015). Notable barge designs include the French firm Ideol's Damping Pool, employed with a 3 MW turbine in Kitakyushu, Japan (Figure 4).

Figure 3: WindFloat 2 MW prototype design from Principle Power, Aguçadoura, Portugal (Source: Untrakdrover)

Figure 4: Ideol's 3 MW Damping Pool barge design, Kitakyushu, Japan (Source: Ole.stobbe.offshore)

Figure 5: Equinor's 2.3 MW spar design; Karmøy, Norway (Source: DoE)

2.1.2 Spar

The spar design is characterised by a relatively small waterplane area and a large vertical distance between its centre of gravity and centre of buoyancy, which stabilises the platform against the aerodynamic thrust-inclining moment (MI), and minimises its heave motions (Wang et al., 2010). As shown in Figure 2b, together the buoyancy force (acting on the centre of buoyancy) and the weight force (acting on the centre of gravity) form a restoring moment (MR), counteracting the inclining moment (MI).

The structure is usually a steel or concrete cylinder with a relatively small radius that is ballasted with water and/or solid ballast to keep the centre of gravity below the centre of buoyancy. Its mooring system is usually catenary or taut spread, with the line material often anchor chains, steel cables or fibre ropes (Butterfield et al., 2007). The technology is adapted from the oil and gas industry, where platforms based on the spar concept have been deployed in water depths of over 2000 m, such as those used in Shell's Perdido Platform in the Gulf of Mexico (Shell, 2018).

The spar concept has been chosen for the world's first commercial floating wind farm: Statoil's (now Equinor) Hywind Buchan Deep, off the North East of Scotland (Box 1) (figure to be inserted). This is a scaled-up version of the 2.3 MW foundation deployed off Karmøy, Norway in 2009 (Figure 5). Other notable designs include Japan Marine United Corporation's Hamakaze, installed with a 5 MW turbine in 2016 as part of the Fukushima Demo 2B.

This concept is most suited to deeper waters (greater than 100 m) as a consequence of its large draft (IRENA, 2016), reducing its operational water depth range and making it more site specific. The large draft also implies that the structure will be towed to the deep water site in a horizontal position, where it will be installed by means of a specialised vessel, assuming the originating port is not in a deep-water location (IRENA, 2016). However, if the port offers sufficiently deep waters, then the structure can be floated vertically and towed to site. The use of specialised vessels for positioning during installation may increase the overall costs, but the manufacturing process is reasonably straightforward, as it is just a long, slender welded structure without complex parts (Carbon Trust, 2015).

2.1.3 Tension leg platform

A TLP is a structure with large buoyancy that is restrained by means of a tension-leg mooring system. These legs are cables, tendon pipes or solid rods, and, when inclined (Figure 2c), the higher tension in the windward leg compared with in the leeward leg creates a restoring moment (MR), which counteracts the inclining moment due to the wind turbine aerodynamic thrust, providing a response to wind and wave loads (ETI, 2015). It involves a shallow draft – smaller than a spar, but larger than a semi-submersible design – with a large centre column and submerged 'arms' to which the tension legs are attached.

The anchors are typically gravity based, suction or pile driven. They are complex to install, as they require certain seabed requirements, making them more site dependent (Carbon Trust, 2015). However, TLPs have a good water-depth flexibility, as they can be installed in relatively shallow to very deep waters (ETI, 2015). Therefore, some TLP designs can be assembled onshore or in a dry dock, requiring the use of specialised vessels only to enable the necessary stability during the installation process (IRENA, 2016).

The TLP is generally considered to be technologically the least developed floating foundation design (DNV, 2012). This, plus its higher installed mooring cost, could explain why it is typically the most expensive design type (Carbon Trust, 2015; IRENA, 2016). Even so, the TLP was one of the very first floating foundations to be deployed in 2008, by Blue H Technologies in Brindisi, Italy (Figure 6). Other notable foundation designers include Germany's Gicon, with their SOF design (Figure 7).

2.1.4 Design variations

Some past, present and future floating wind projects present variations on the typical single horizontal axis turbine, mounted on a single foundation. There are three main variations. The first is the installation of multiple turbines on a single semi-submersible foundation, as employed by the Swedish firm Hexicon's design and the Spanish firm EnerOcean with their W2Power design, which is due for part-scale commissioning in mid-2019. The second is the installation of turbines other than the market-dominant horizontal-axis wind turbine, such as Makani's airborne wind energy system 'kite' design or SeaTwirl's vertical-axis turbine. The third is the integration of multiple sources of generation on a single floating platform, such as the Danish firm Floating Power Plant's Poseidon P80, which combines a floating semi-submersible foundation with a wave-power convertor.

Figure 6: Blue H Technologies' concept, deployed off Brindisi, Italy (Source: Green Storm 7)

Figure 7: TLP concept from Gicon SOF (Source: GICON GmbH)

2.2 Advantages and disadvantages of floating wind

It is important to outline floating wind's advantages and disadvantages versus traditional forms of fixed-foundation offshore wind projects.

2.2.1 Advantages

Floating wind's core advantage is that it enables the capture of wind resources located in waters currently too deep to be considered cost-effective. This is important for two main reasons. First, the most suitable offshore wind sites located at near-shore – shallow water sites – are gradually becoming less available as offshore wind developers have already taken advantage of these 'low-hanging fruit' (Carbon Trust, 2015). Floating wind technology opens up deeper waters and creates opportunities for developers to take advantage of deep-water sites, both near- and far-offshore. Second, deeper, more remote waters can offer higher average wind speeds, in turn improving capacity and potentially reducing the LCOE of offshore wind.

Installation costs can also be reduced, as turbines can be mounted onto their foundations at suitable port facilities and floated to the site to be installed, meaning that tugboats can be employed instead of expensive heavy lifting vessels (Paul Sclavounos, 2012). This can potentially increase the flexibility of the installation procedure too, widening the typically very small 'weather windows' associated with installing conventional foundations due to the quantity of offshore assembly involved (Topham and McMillan, 2017).

Plugging and unplugging methods for the electrical and mooring systems can allow the structure to be towed back to port for O&M, also helping to reduce costs as no specialised vessels are required (Carbon Trust, 2015). This entails a reduction in the health and safety risk, as less work is performed offshore (Topham et al., 2019). Finally, floating wind can also result in lower impact on the marine environment, as the seabed undergoes less harmful 'preparation'. This is due to the use of moorings instead of a fixed structure, which require less seabed penetration (Bailey, Brookes and Thompson, 2014). The Royal Society for the Protection of Birds has also identified floating wind technology as a potentially important means of reducing the risk of bird strikes, since floating wind platforms can be located further offshore in deeper water areas (RSPB, 2016).

2.2.2 Disadvantages

Floating wind is not without its drawbacks. The biggest single challenge to deployment of floating wind is the higher capital cost versus fixed-bottom offshore wind. This is especially true in the North Sea, which has an abundance of appropriate sites for offshore wind generation in water depths of less than 60 m. Other key challenges include:

1. **Installing and operating wind farms in deeper waters that are much further offshore**. Here conditions are significantly harsher than near-shore, with more intense wave action and higher winds which can together cause extensive damage (Butterfield et al., 2007).
2. **Most designs utilise existing offshore turbines originally designed for fixed-bottom use**. This creates a requirement for specialised turbine control systems that 'tune' the performance of the turbine to account for additional movement associated with a floating turbine[6] (Savenije and Peeringa, 2014). Novel pitch motion controllers have already been installed at the Hywind project (Equinor, 2018b).
3. **The mechanical/electrical design, construction and installation of power cables in deep water** to transmit the electricity back to land can entail major expense (Lakshmanan, Liang and Jenkins, 2015). There is also the challenge of mating cable connections with a floating and thus moving foundation, as well as implementing an unplugging system that allows the O&M procedures to take place onshore.
4. **Limited number of suitable port facilities available for the construction, assembly and floating of foundations** (Matha et al., 2017), which could eventually produce a bottleneck if the sector grows rapidly. Essentially, the width and depth available at the port limit the maximum width and draft of the platform that can be assembled. Specialist equipment may also be required.

6 This can be implemented in the control loop that controls the blades' pitch angle and potentially other loops (e.g. torque loop). It can include changes in:
   a. the notch filter, employed at rigid body frequencies (i.e. pitch/roll) to prevent instabilities/excessive pitch action;
   b. in the gains at the Proportional Integral (PI) controller, which are reduced to avoid rigid body instabilities, generally at the cost of more power/rotor speed variation; and
   c. specialised feedback loops that are used for nacelle acceleration feedback to actively damp floating rigid body motions.

3

Methodology

This study examines both past and future trends across the floating wind market by assessing project-level data, aggregating this to a national and then global level. The following characteristics were sought from the 60 floating wind projects we identified:

- Commissioning/decommissioning date
- Project status
- Country of deployment
- Depth (m)[7]
- Distance to shore (km)
- Capacity (MW)
- Number of foundations
- Number of turbines
- Turbine capacity
- Hub height
- Foundation design
- Foundation developer
- Developer nationality

To populate our project database, we collected data via a two-tier approach. First, publicly accessible databases containing floating offshore wind project data were assessed, most notably 4COffshore[8] (2018b), Quest FWE (2019a), RenewableUK's Project Intelligence (2019b) and US Department of Energy's wind market report (2018a). Second, to fill any data gaps and triangulate the data from these databases, data was collected directly from project developers' websites or other reputable sources (e.g. trade publications, press releases etc.). If there was conflicting information, we prioritised information provided directly by the project developer or floating wind foundation designer. Projects were only included in our analysis if we could identify reliable information on the following characteristics: (1) project location; (2) installed capacity; and (3) foundation type. Because of the lack of data on Chinese floating wind projects, they are excluded from the analysis. It is clear that projects are being developed in China, but we do not have sufficient confidence that we can report on their characteristics or status in any meaningful way. Project data is correct up to 1 June 2019.

Costs have been omitted from this report, following an initial analysis that showed a lack of transparency in the way in which they had been reported. For example, most costs were cited without any indication as to whether the costs included operational and/or maintenance costs, and some were merely indications of government and/or private funding, rather than total project costs. As such, large discrepancies between the costs of specific projects were reported across different sources and this rendered any meaningful comparison impossible.

3.1 Project status

Our research examined the status of projects to ascertain the current size of the floating wind market, as well as the scale and maturity of projects in the development pipeline. In the order of most to least mature, projects were categorised as follows:

1. Decommissioned
2. Operational
3. Construction
4. Consent authorised
5. Applied for consent
6. Early planning

Projects at the early planning stage are the least mature and have yet to apply for consent. Given their early stage, many of these projects do not have a clear, targeted commissioning date. There are a handful of projects that have received consent, but with no clear timeframe for deployment, having become delayed for one reason or another. Examples include the UK's Dounreay Tri and Forthwind projects. In these instances, the projects were reclassified as at the early planning stage.

3.2 Projects by country

The report defines the nationality of projects in two different ways. The first is based on where the floating wind turbines have been or will be installed. The second is by the nationality of the country responsible for developing the floating foundation, referred to as the foundation designer. The latter's nationality is determined by the country where the lead foundation designer is headquartered and relates to the current owner of the intellectual property (IP), therefore not accounting for any transfer of IP from one nationality of company to another via mergers and acquisitions, etc. We also acknowledge that design and/or manufacturing can take place in a country other than that where the company is headquartered.

3.3 Foundation types

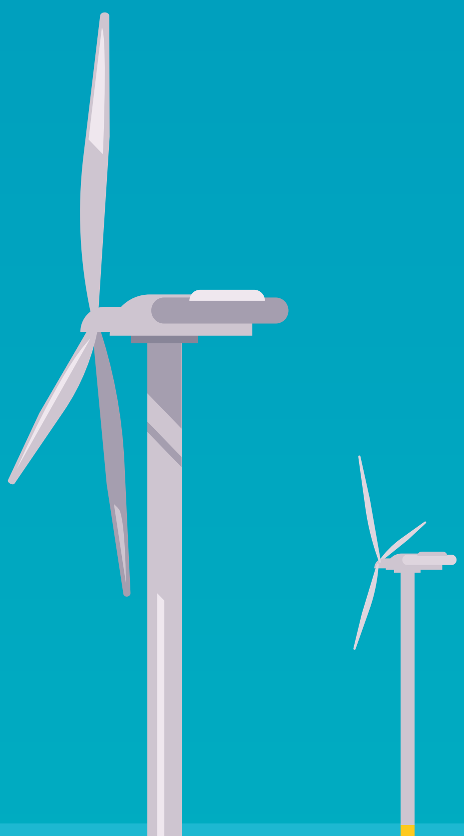
We use the three categories of foundation type as presented in Section 2.1. We regard semi-submersible and barge foundation designs as closely related to one another, as they both achieve stability against the wind turbine thrust-inclining moment through their waterplane area (see Section 2.1). Consequently, we use the single term semi-submersible as a 'catch all' category that covers both semi-submersible and barge foundation types. Where projects employ more than one foundation type (e.g. spar and semi-submersible) we have split these into sub-projects by foundation type.

7 In some instances, depth is given as a range due to tidal range. Consequently, we take the mid-point of this range as the project's mean water depth.

8 Subsequent to our initial data collection, 4COffshore ceased to provide all their data free. Instead, they made only a portion of their data available via a freemium service. Consequently, some of the data used may no longer be publicly available.

4

International market leaders in the floating wind industry



4.1 Project pipeline

Of the 60 projects identified (Figure 8), 20% (n=12) are operational, whilst another 17% (n=10) have already been decommissioned. Most of the latter were temporary, small-scale demonstration projects. Almost a quarter of projects are in the floating wind 'pipeline' (n=14), including five which are under construction, four which have been granted consent and another five which have applied for consent. In total, 24 projects are at an early stage of planning and were yet to submit an application for consent[9] – 40% of the total.

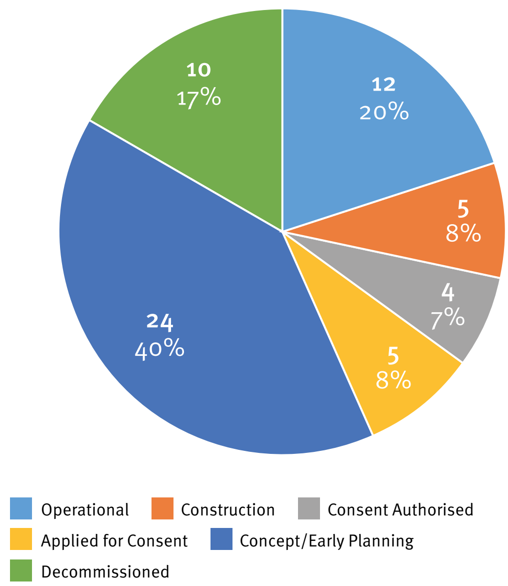


Figure 8: Current status of floating wind projects worldwide

4.2 Leader by nationality of deployment

4.2.1 Past and present

In total, 22 floating offshore wind projects have at some point already been commissioned. Japan has the greatest cumulative experience, having delivered a total of seven projects as of 2018, with USA and Norway the next most experienced with three projects each.

Today, the number of operational projects is higher than it has ever been, with 12 projects now commissioned. Japan leads with five projects, with France and the UK runners-up with two projects each. These countries, however, were not always the front-runners. Back in 2008, the first projects were delivered by Italy and Denmark,[10] with Norway entering the field in 2009 and the USA and Portugal in 2010. Given the immature nature of the technology ten years ago, these early projects were low-capacity demonstration projects, and some have since been decommissioned (Figure 9). Interestingly, of the 'first-movers', both Denmark and Italy have failed to install any new projects over the past few years, and only Norway and the USA continue to have operational projects today. More recently, growth has mostly been driven by Japan, alongside new entrants such as Sweden, France and the UK.

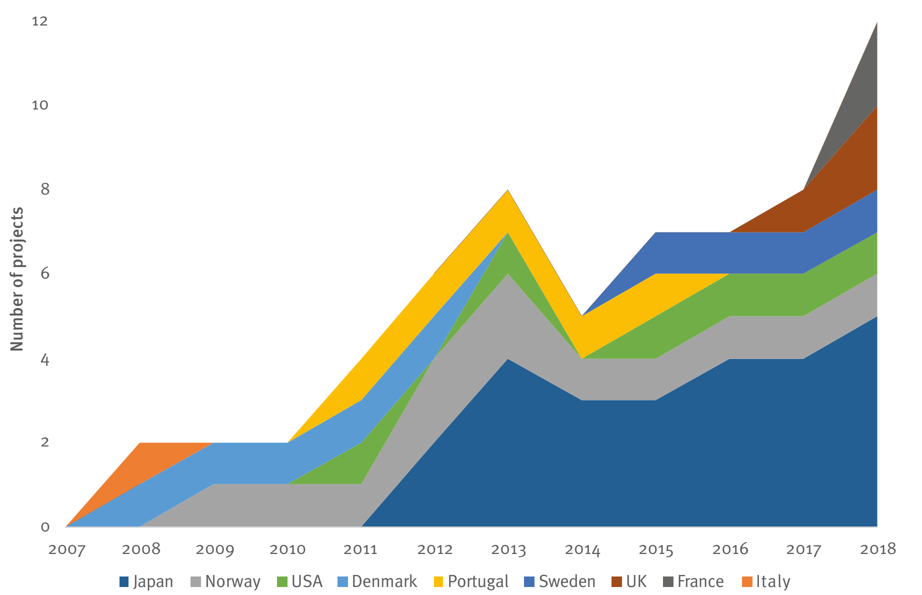


Figure 9: Cumulative number of projects installed by nationality

NOTE: Countries ordered by cumulative number of years with operational projects. A reduction in project number is a function of decommissioned projects.

9 We have identified some projects, most notably the UK's Dounreay Tri and Forthwind projects, which have been granted consent but appear to have been postponed indefinitely. They are therefore classified as early planning.

10 Brindisi in Italy and Poseidon P37 in Denmark.

4 International market leaders in the floating wind industry

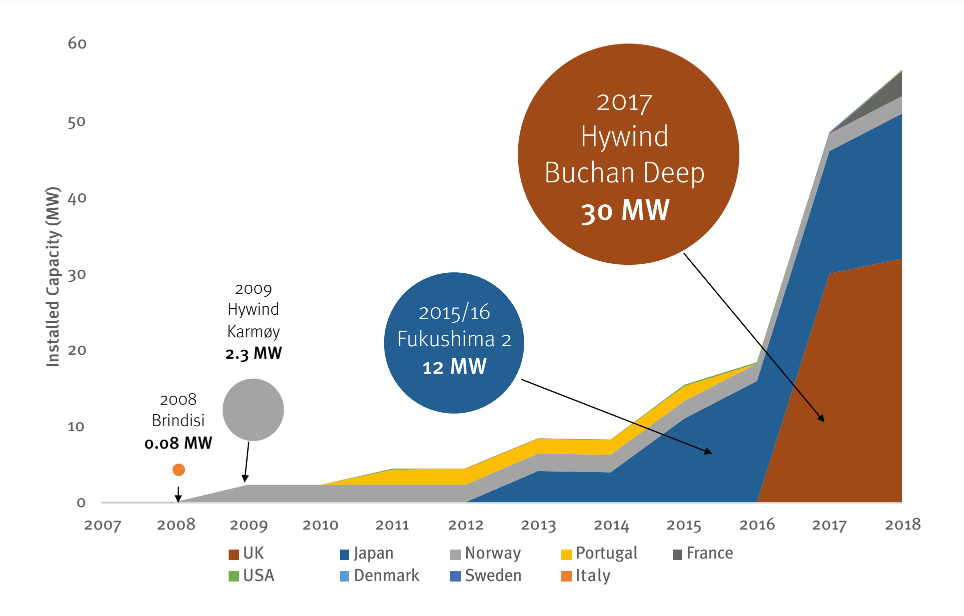


Figure 10: Cumulative installed capacity by nationality.

NOTE: Record-capacity installations shown by circle area and are sized proportionally.

Figure 10 presents the historical cumulative installed capacity of floating wind projects by nationality, with record-capacity installations shown proportionally by the areas of the circles. Whilst the number of projects has gradually increased (Figure 9), we see a dramatic growth in installed capacity, standing at 57 MW in 2018. Whereas Norway, Japan and USA have led in terms of number of projects, the UK and Japan are clear leaders in terms of installed capacity. They are home to 32 MW and 21 MW of operational capacity, accounting for 56% and 37% of global capacity respectively.

We also note a significant growth in the size of projects being commissioned. In 2008, the largest installation was an 80 kW demonstration device at Brindisi in Italy. This jumped markedly in 2009 with a 2.3 MW installation at Karmøy in Norway. That remained the largest installation until 2015, when a two turbine 12 MW array was installed at Fukishima in Japan. By 2017, Equinor had installed the world's largest floating wind array – the five turbine 30 MW Hywind at Buchan Deep, 25 km off the East Coast of Scotland (see Box 1). The growth in project size is a function of both an increase in the number of turbines per project and the capacity of the turbines being installed (Section 5.2).

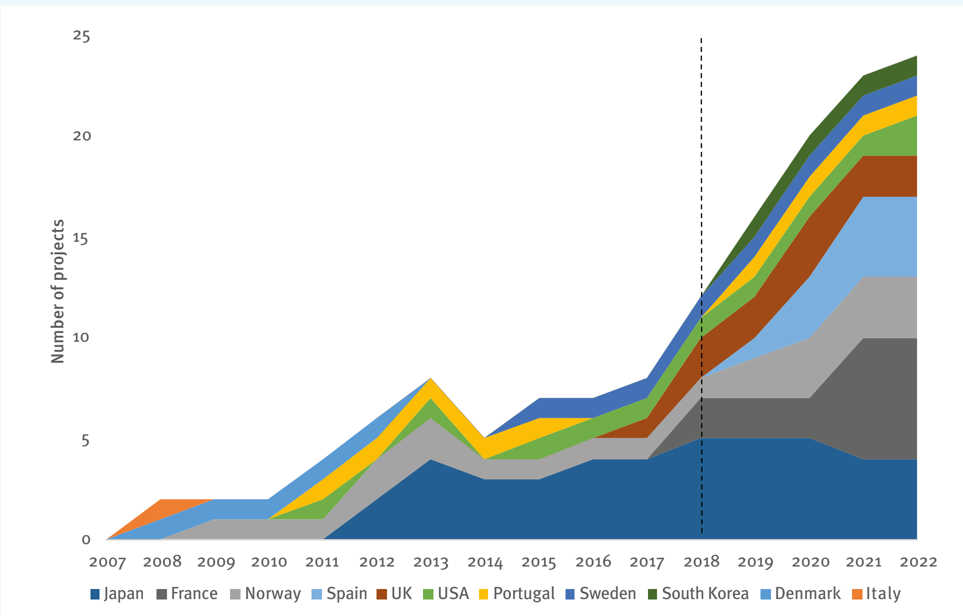


Figure 11: Cumulative number of projects to 2020 by nationality – excluding projects in early planning

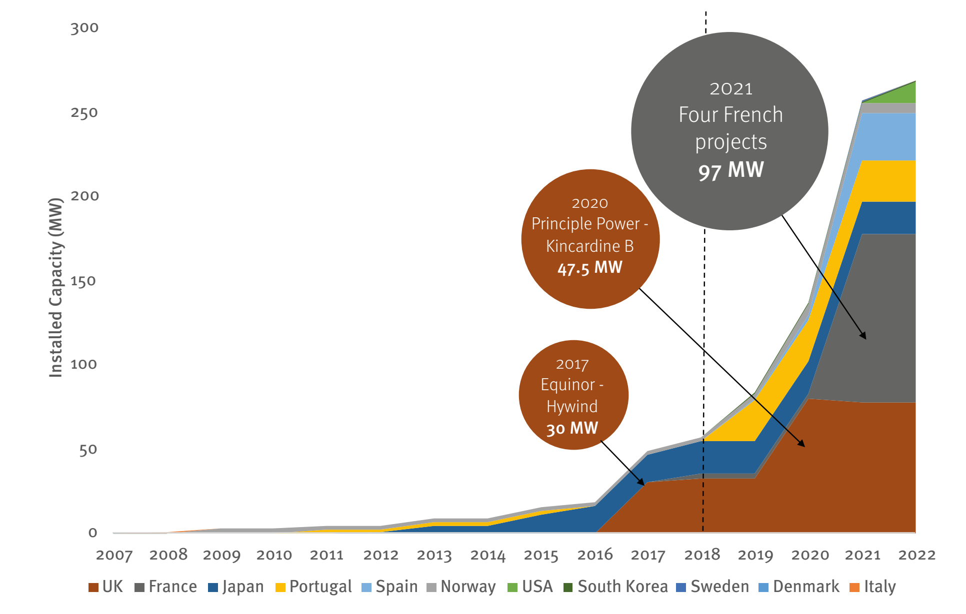


Figure 12: Cumulative installed capacity to 2022 by nationality – excluding projects in early planning.

NOTE: Record-capacity installations shown by circle area and are sized proportionally.

4.2.2 Future

4.2.2.1 Excluding early planning

Looking out to 2022 and excluding concept/early planning projects from the analysis, we find the number of projects could grow from 12 in 2018 to 26 projects, with no further additional capacity entering the water thereafter (Figure 11). Taking this view, new projects do not emerge from Japan; the current leader in terms of project numbers. Instead they are led mostly by France, Norway and Spain. By 2022, France leads with six projects, a quarter of the global total, with Japan and Spain joint second with four projects each and Norway with three. Both Spain and South Korea are new entrants post-2018, with Portugal re-entering the market, together adding further competition to the marketplace.

Turning to future installed capacity, and only taking into account projects that have at least applied for consent, the global total installed capacity is expected to reach 268 MW by 2022 – almost five times that of today (Figure 12).

If all these projects were commissioned, the UK would lose its international lead to France, accounting for 78 MW versus 100 MW in France, and together accounting for two thirds of all capacity. The remaining third of global capacity is largely made up by Spain (27 MW), Portugal (25 MW), Japan (19 MW) and the US (12 MW). The largest installation that has at least applied for consent is Kincardine B in the UK, a five-turbine project totalling 47.5 MW (Box 2). However, it is worth noting that there are five projects of 24-25 MW in this category too, four of which would be in French waters.

4.2.2.2 Early planning

If the analysis is expanded to include early-stage projects, a further 24 projects could potentially come online during the mid-to-late 2020s (Figure 13). Here we find that the UK leads with seven early-stage projects, roughly a quarter of the total, closely followed by the US with five. Other notable national developers[11] in the medium- to long-term include Japan, Spain, France and Norway.

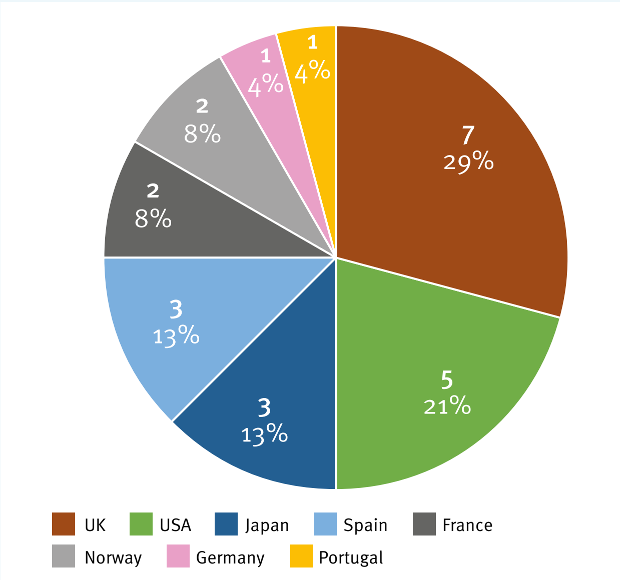


Figure 13: Number of projects by nationality of deployment – early-planning projects only

Note: Subsequent phases to projects are counted as separate, stand-alone projects.

11 We note that South Korea has recently announced plans to grow its floating offshore wind sector significantly via a slew of memorandums of understanding (Quest FWE, 2019e) but project details are unclear at present, especially which foundation designs will be used. Consequently, the projects did not meet our criteria for inclusion, as outlined in the methodology, and are omitted from the analysis.

4 International market leaders in the floating wind industry

Looking forward, 5.9 GW of installed capacity is at an early stage of planning, versus 57 MW today. To provide a sense of scale, this is almost 70% of the UK's current installed offshore wind capacity. If all these projects come to fruition, the USA will become the clear market leader, with 2.2 GW installed (Figure 14), accounting for 37% of all the installed capacity. The UK would be a close second with 1.9 GW (33%), Japan with 1 GW (18%) and France with 510 MW (9%). The UK's capacity is attributed mostly to three projects from Denmark's Floating Power Plant and two from France's Ideol.

It is important to note that this surge in installed capacity is due to a handful of extremely ambitious planned projects that are an order of magnitude larger than existing projects and are thus at a high-risk of never being commissioned (Table 1). It is important to note that none of these ambitious projects have a clear estimated date for commissioning.

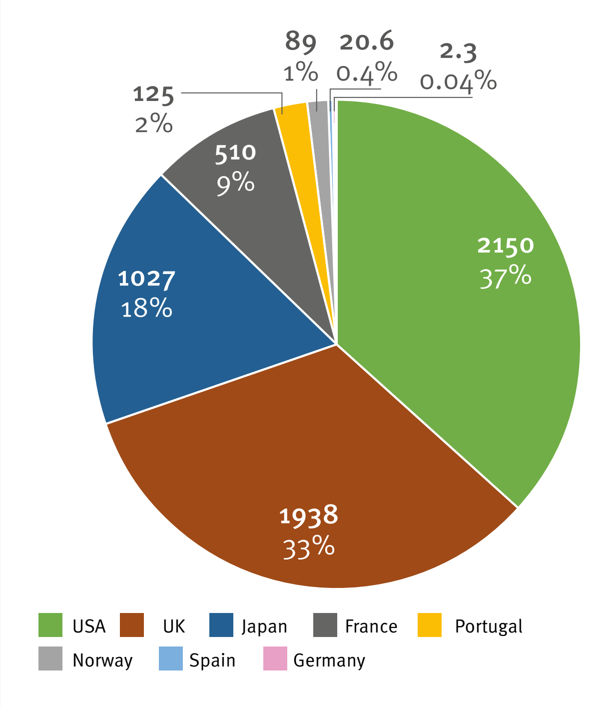


Figure 14: Installed capacity by nationality of deployment – only early-planning projects (MW)

Table 1: Top 10 early stage planned projects by capacity (adapted from US Department of Energy, 2018b)

Project name	Host nation	Capacity (MW)	Lead project developer	Floater	Floater designer	Designer nationality	Foundation type
Ideol/Atlantis Energy 1.5 Floating Project	UK	1400	Atlantis Energy and Ideol	Damping Pool	Ideol	France	Semi-sub
Fukushima Phase 3	Japan	1000	Fukushima FORWARD Consortium[12]	N/A	N/A	N/A	Semi-sub
Morro Bay	USA	650-1000	Trident Winds	Windfloat	Principle Power	USA	Semi-sub
EolMed – Ideol & Quadran	France	500	Quadran and Ideol	Damping Pool	Ideol	France	Semi-sub
Oahu North, Hawaii	USA	400	Alpha Offshore Wind	Windfloat	Principle Power	USA	Semi-sub
Oahu South, Hawaii	USA	400	Alpha Offshore Wind	Windfloat	Principle Power	USA	Semi-sub
Oahu West, (Progression) Hawaii	USA	400	Progression Energy	Windfloat	Principle Power	USA	Semi-sub
FPP Dyfed	UK	224	Floating Power Plant and DP Energy Ireland	Poseidon	Floating Power Plant	Denmark	Semi-sub (+ wave power)
FPP Katanes	UK	184	Floating Power Plant and DP Energy Ireland	Poseidon	Floating Power Plant	Denmark	Semi-sub (+ wave power)
Northern California Floating Offshore Wind Project	USA	125	Redwood Coast Energy Authority	Windfloat	Principle Power	USA	Semi-sub
Windfloat Atlantic Phase 2	Portugal	125	WindPlus S.A.[13]	Windfloat	Principle Power	USA	Semi-sub

12 Fukushima offshore wind consortium consists of 11 companies. These include Marubeni Corporation (Project integrator), the University of Tokyo, Mitsubishi Corporation, Mitsubishi Heavy Industries, Japan Marine United Corporation, Mitsui Engineering & Shipbuilding, Nippon Steel & Sumitomo Metal Corporation, Ltd., Hitachi Ltd., Furukawa Electric Co., Ltd., Shimizu Corporation and Mizuho information & Research (Fukushima Offshore Wind Consortium, 2013).

13 WindPlus consortium is a subsidiary of EDP Renováveis (79.4%), Repsol S.A. (19.4%) and Principle Power Inc. (1.2%) (EIB, 2018).

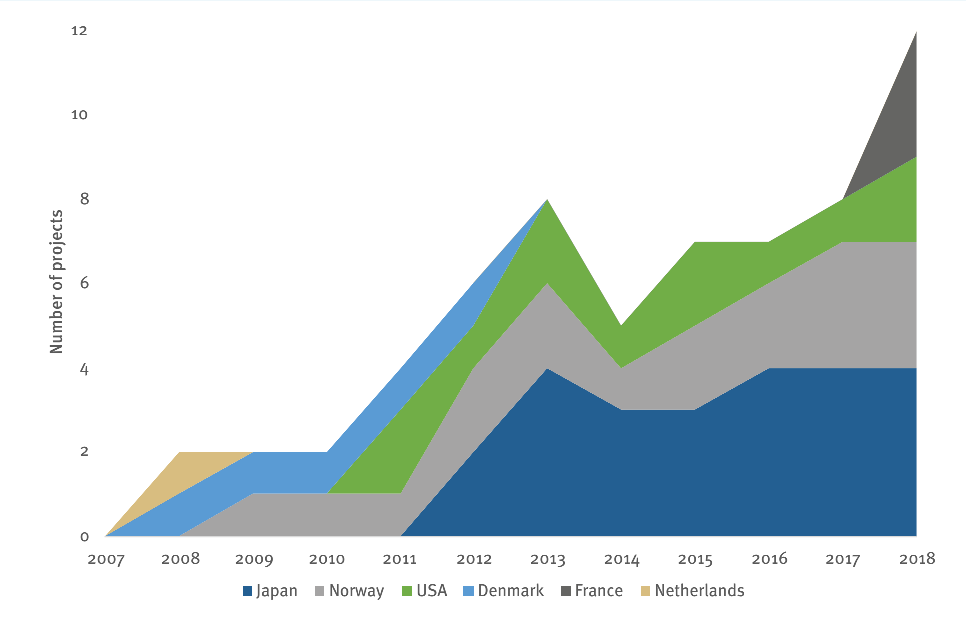


Figure 15: Cumulative number of projects by foundation technology designer nationality.

NOTE: Makani project in Norway excluded because it is unclear what the nationality of the foundation developer is.

4.3 Leaders by nationality of foundation technology

In this section we examine the nationality of floating wind foundation designers, as determined by where they are headquartered. The rationale is to uncover where the majority of the IP relating to foundation design resides, considering that the design and supply of foundation technology represents a significant proportion of the offshore wind industry supply chain.[14]

4.3.1 Past and present

In terms of the number of projects, Japan, Norway and USA are the international leaders of foundation design (Figure 15). For installed capacity, Norwegian foundation designers account for over half of the current installed capacity (Figure 16), with Japan a relatively close second. Norway's clear lead is really accounted for by a single project – the 30 MW Hywind Buchan Deep in Scotland.

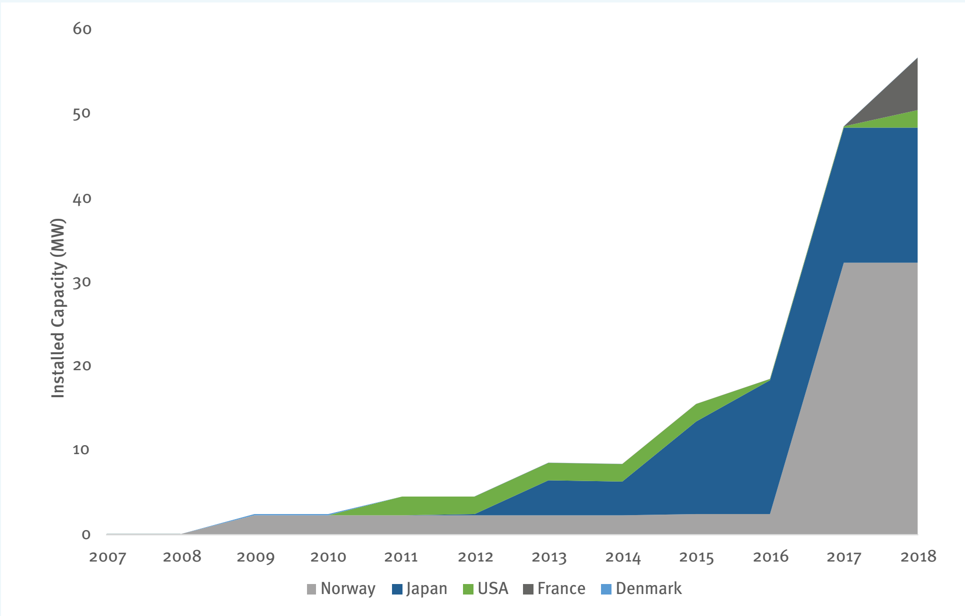


Figure 16: Cumulative installed capacity by foundation technology designer nationality.

14 In some cases, the developer may sub-contract manufacturing to another company but retains the IP associated with the foundation design.

We are also able to disaggregate the data further to consider which firms have led the market to date. Norwegian firm Equinor is the clear leader, and the only firm to have delivered a floating wind array at scale (Box 1). Japanese firms also have experience of installing commercial-scale turbine foundations. What is clear from Table 2 is the variety of firms engaging in this sector, with a mix of both multi-nationals and small and medium-sized enterprises (SMEs), as well as from both the wind power sector and elsewhere (e.g. shipbuilding, construction, oil and gas).

Table 2: Top 10 foundation designers – operational and decommissioned projects only

Foundation designer	Nationality	Scale of company	Primary sector	Nos. of projects	Nos. of foundations	Total capacity
Equinor	Norway	Multi-national	Oil and gas	2	6	32
Mitsubishi Heavy Industries	Japan	Multi-national	Engineering	1	1	7
Ideol	France	SME	Floating wind	2	2	5
Japan Marine United Corporation	Japan	Multi-national	Shipbuilding	1	1	5
Principle Power	USA	SME	Floating wind	2	2	4
Toda	Japan	Multi-national	Construction	2	2	2.1
Kyoto University, Sasebo Heavy Industries, Toda Corporation and Nippon Hume	Japan	(Consortium)	(Consortium)	1	1	2
Mitsui	Japan	Multi-national	General trading companies	1	1	2
Eolink	France	SME	Floating wind	1	1	1.2
Keuka Energy	USA	SME	Floating wind	2	6	0.275

4.3.2 Case studies of UK content

We find that UK floating wind foundation designers have yet to see their devices deployed at scale in the ocean environment.[15] To expand our analysis of UK content across the wider supply chain, we examine the two UK-based projects of Hywind (Box 1) and Kincardine (Box 2). We find that, whilst UK firms are present, especially at the design and operational stages, non-UK firms cover the majority of these projects' supply chains. A full supply-chain breakdown is provided for both cases in Appendix A.

15 We acknowledge that some UK-based designers do exist, such as Tetrafloat, but they have not deployed at scale. Atkins has also played a critical role in delivering aspects of various floating wind designs and projects as an engineering partner, such as Hexicon's device and Principle Power's WindFloat.

Box 1

Case study of Hywind Scotland Pilot Park, Buchan Deep, UK

Located about 25 km off Peterhead at Buchan Deep, in the North East of Scotland, Hywind was the world's first commercial scale floating wind array when it was commissioned in 2017.

Buchan Deep incorporates five 6 MW turbines, mounted on Hywind spar foundation. The turbines rise 175 m above sea level and are submerged to a depth of 78 m. It was developed by the oil and gas company Equinor, who own 75% of the development.

The Hywind spar floating-turbine technology was first employed as a part-scale prototype in Trondheim, Norway in 2005, before it was installed by Equinor in 2009 in the North Sea as the world´s first floating full-scale wind turbine.

The vast majority of the turbine components were shipped to Stord in Norway for assembly (Figure 17) before the turbines and foundations were mated off the Norwegian coast and then shipped to the UK. The project is also notable for integrating 1 MW of grid-connected battery storage through the BATWIND initiative (Equinor, 2018a).

The project costs are estimated at £210m for capital expenditure (CAPEX) and £84m for operational expenditure (OPEX) (Quest FWE, 2019b). To help cover these the project was successful in securing subsidy from the Renewable Obligation for a 20-year period (Section 8.1.2).

UK companies have played an important role in delivering the Hywind array. Their roles have covered project planning and providing survey (e.g. geotechnical, environmental, meteorological) and technical due diligence expertise. UK firms such as Global Energy Group supplied the 15 suction anchors, which were installed by the UK's TechnipFMC. UK firms such as Subsea 7 and Balfour Beatty installed the offshore and onshore cabling respectively. Finally, specialist installation cranes were provided by Granada Material Handling, whilst monitoring services such as LIDAR (Wood Group) and mooring line loading (Strainstall/James Fisher & Sons) were also supplied by UK firms.

Even so, out of the 36 companies directly involved in Hywind's supply chain, only 13 companies were UK-headquartered. Instead, the majority of core services and technologies were provided by other European countries.

Ten of the companies, including Equinor, originate from Norway. These provide logistics, assembly, installation and operational services, as well as some components (e.g. cables). Spanish firms were also prevalent, not least in manufacturing Equinor's Hywind floating foundations (Navantia-Windar), turbine towers (Navacelle) and mooring lines (Vicinay Marine), whilst German firm Siemens supplied the turbines, albeit with significant UK-based manufacturing capacity. Other European countries were also involved, such as Poland (forging), Italy (turbine-foundation mating) and France (cable buoyancy). The only non-European firms with significant involvement was the UAE's Masdar, which owns 25% of the project, and Metocean Services International.

Figure 17: Two of Equinor's five 6 MW turbines being prepared in Stord, Norway, to sail off to Peterhead, Scotland (Source: Terje Aase / Shutterstock.com)

Box 2

Case study of Kincardine Offshore Windfarm Project, UK

Located 15 km south-east of Aberdeen, off the east coast of Scotland, Kincardine is the UK's second major floating wind project.

The lead developer, Kincardine Offshore Windfarm Ltd. (KOWL), was formed by Pilot Offshore Renewables Limited (PORL) and Atkins Ltd. PORL is a joint venture between UK firms MacAskill Associates Limited and Renewable Energy Ventures (Offshore) Limited. Atkins relinquished its stake in the project and now KOWL is majority controlled by Spanish firm Cobra, part of the ACS Group (KOWL, 2017, 2018).

Figure 18: Kincardine demonstration turbine being towed (Source: Bourbon Offshore / Remco Bohle Photography)

The project is split into two phases. The first phase was commissioned in 2018, including a 2 MW V80 Vestas turbine, integrated with a semi-submersible Windfloat foundation from US firm Principle Power (Figure 18). The turbine is due to be decommissioned in 2021. The project's costs are estimated at £23m for CAPEX and £9m for OPEX (Quest FWE, 2019c). The project secured subsidy from the UK's Renewable Obligation for a 20-year period.

Phase 2 is fully consented and expected to include five MHI Vestas 164 9.5 MW turbines, creating a further 47.5 MW of capacity. This is a new Vestas turbine that will not be available until late 2019, meaning installation is not possible until early 2020. It also points to how the floating wind sector is employing cutting-edge wind-turbine technology.

The project is expected to operate for an estimated 20 years. Costs are estimated at £325m for CAPEX and £130m for OPEX (Quest FWE, 2019d) .

A similar story is seen to Hywind Buchan Deep in terms of UK-supply-chain (Box 1) content. Only eight of the 21 companies responsible for delivering the project were UK based. UK firms mostly delivered services, including surveying (Atkins, Fugro), cable installation (Global Energy), O&M (Kinetic Renewables Services) and metocean (Partrac). FirstSubSea did, however, provide technology in the form of the platform-mooring connectors. Correll Services, which was responsible for jointing and termination of export cabling, is based in the UK but has recently been acquired by a German company.

Turning to non-UK European content, we find the project company is majority owned by the Spanish engineering firm ACS Group, with UK firms retaining a minority stake. Other Spanish companies involved include Navantia and Windar for foundation fabrication, Vicinay Marine for mooring chains and SENER for oversight of production and procurement. Other European companies cover different supply chain activities, including moorings and anchors (Dutch firm Vryhof Anchors), export cables (Italian firm Prysmian Group), and project coordination and installation (French firm Bourbon). Non-European firms were also key, including US firm Principle Power for the floaters and part-European firms like MHI Vestas for the turbines. The latter has significant UK manufacturing capacity.

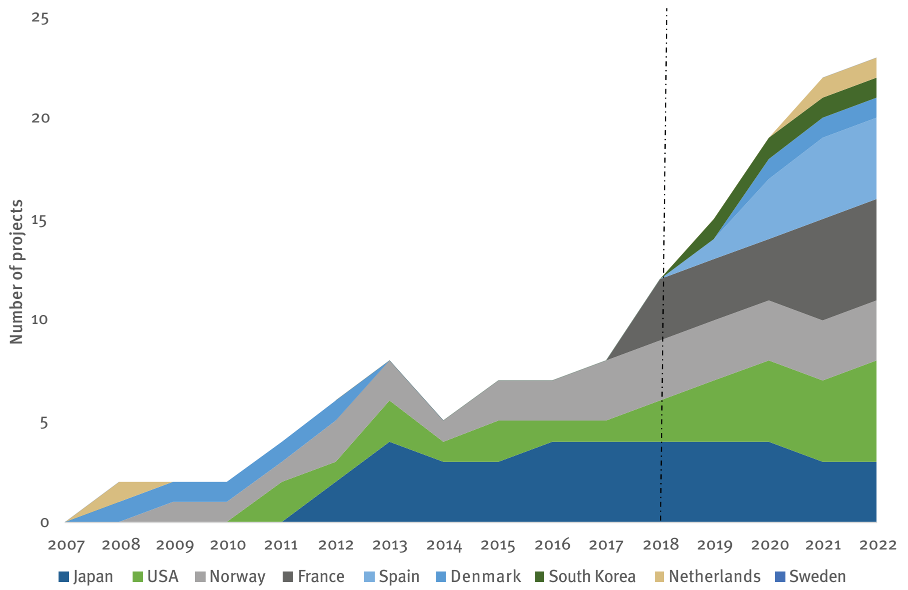


Figure 19: Cumulative number of projects by foundation technology designer nationality to 2022 – excluding projects in early planning

NOTE: Projects without a known technology designer excluded.

4.3.3 Future

4.3.3.1 Excluding early planning

Figure 19 shows all planned projects that have at least applied for consent, split by the nationality of foundation designer. It shows how Japan and Norway continue to play a key role in foundation design, with three projects each and 13% of total projects by 2022. However, it is the USA and France that take the lead, each accounting for 22% of projects (n=5), with Spain accounting for 17% (n=4). France and Spain constitute new entrants, as they do not currently have any of their floating designs operating in the water. They are expected to be joined by other new entrants, including the Netherlands and South Korea, all with one project each.

Turning to installed capacity by foundation designer nationality, Figure 20 shows how the USA is expected to overtake Norway as market leader from 2020, with 109 MW installed by 2022 – almost 40% of the market. France too overtakes Norway with 55 MW and a 20% share by 2022, versus 32 MW and a 12% share for Norway. Other important players include Spain (27 MW) and Japan (16 MW). The UK is once again notably absent, with no UK foundation concepts planned for deployment.

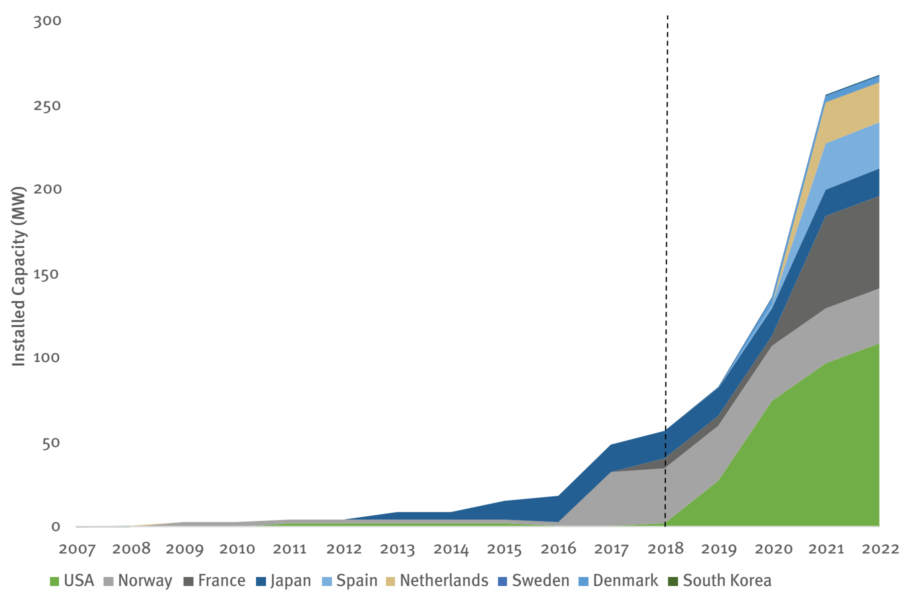


Figure 20: Cumulative installed capacity by foundation technology designer nationality to 2022 – excluding projects in early planning

NOTE: Projects without a technology designer excluded.

4.3.3.2 Early planning

Focusing on just early stage planned projects (Figure 21), the USA takes a strong lead over its rivals, responsible for designing the foundations for seven future projects. Danish designers are planning four projects and French designers three, with Sweden, Spain and Norway planning two each.

Turning to installed capacity (Figure 22), we again see the USA as the dominant force by 2022 with 2.3 GW installed, accounting for 39% of the market. France is a close second, with 2 GW (34%) and Denmark third with 424 MW (7%). We note that 1 GW and 17% of installed capacity have yet to declare a preferred foundation designer. Once declared, that could substantially change these countries rankings.

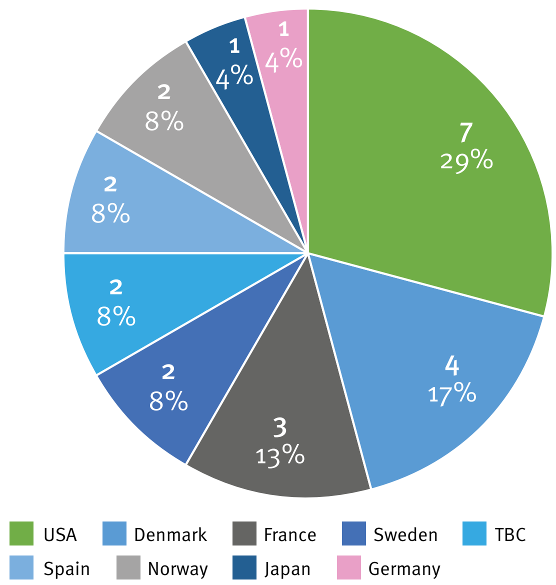


Figure 21: Number of projects by nationality of designer – early planning projects.

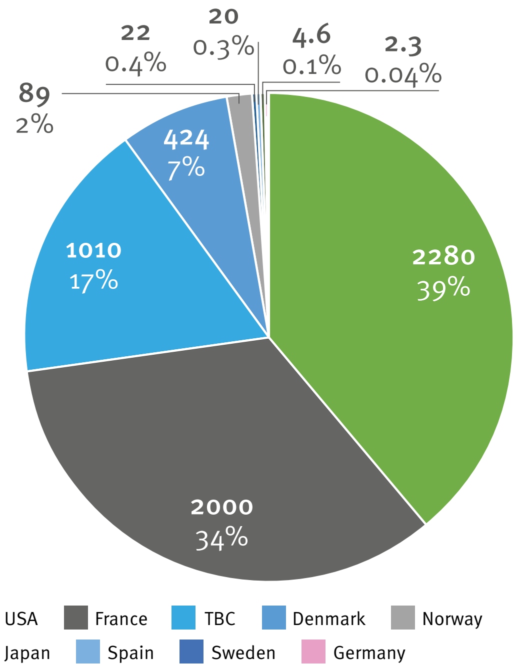


Figure 22: Installed capacity by nationality of designer – early planning projects (MW)

NOTE: Subsequent phases to projects and projects the employ more than one type of foundation design are counted as separate, stand-alone projects. Projects without a named foundation developer listed as TBC.

5

Technological trends in floating wind

The first describes recent and future trends in the deployment of the three main competing floating wind foundation types (see Section 5.1). The second analyses technological trends considered to be proxies of technological maturity (see Sections 5.2 and 5.3), including: 1) size and power rating of floating turbines; 2) the number of turbines per array; and 3) distance from shore and depth of water.

5.1 Foundation types

5.1.1 Past and present

In this section, an analysis of the most adopted floating foundation design for offshore wind turbines is presented. Convergence around a dominant design has been identified as an important stage of a technology market's maturation (Abernathy and Utterback, 1978). However, each type of floating wind foundation (Section 2.1) offers different strengths and weaknesses with respect to the environmental context it is being deployed in. So instead, we are likely to see a handful of foundation types emerge for floating wind, each best suited to their niche context, in relation to water depth, supply chain, infrastructure, etc.

The evidence supports the view that a number of foundation types will emerge, with both operational and decommissioned projects broadly split between spar (n=12 52%) and semi-submersible (n=10 44%) technologies since 2008, and TLP accounting for just one project (4%) (Figure 23). The reasons for TLP's lack of market penetration are not clear, and further research is needed to explain why. Figure 23 illustrates how, in 2018, semi-submersible had the upper hand, accounting for eight operational projects and 62% of the market, versus five spar projects (38%).

The picture, however, is reversed if we consider the state of the market in 2018 by installed capacity (Figure 24). Spar clearly dominates, with 39 MW and 69% of the market versus 17 MW (31%) for semi-submersible. The dominance of spar over semi-submersible is almost entirely due to the design choice of Equinor and their spar Hywind design for the 30 MW Buchan Deep array. TLP accounted for nothing in 2018, and was limited to a very small 80 kW year-long demonstration project at Brindisi, Italy in 2008.

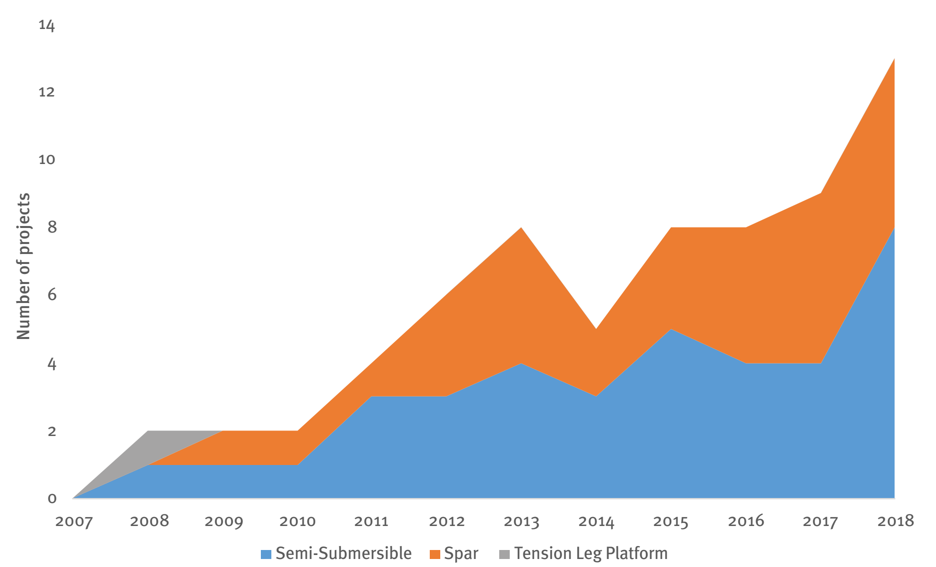


Figure 23: Cumulative number of projects by foundation design type

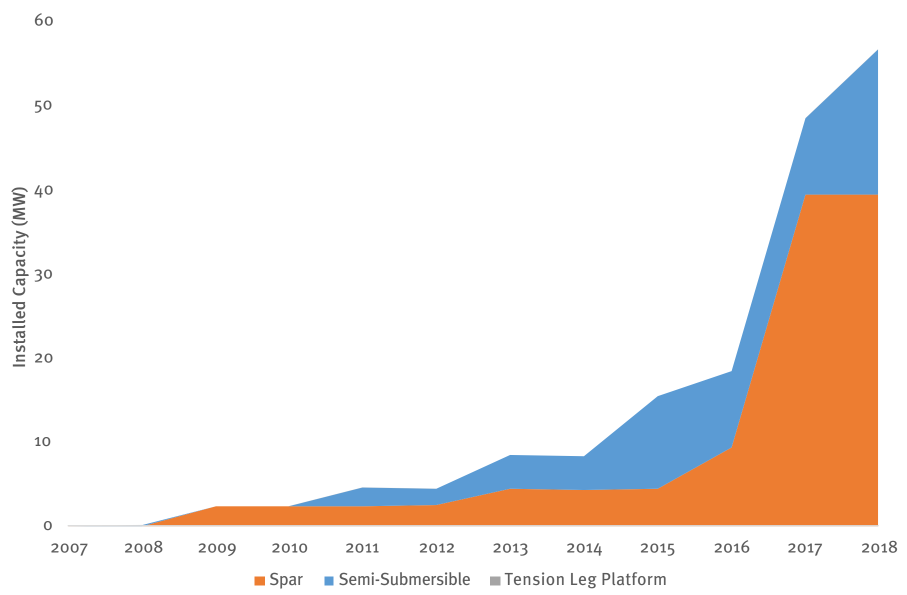


Figure 24: Cumulative installed capacity by foundation design type

It is important to note that there are a number of projects that present design variations on a single horizontal-axis turbine on just one floating foundation. For example, two of the semi-submersible projects included multiple forms of generation: 1) Kyushu University's Windlens, with wind and integrated solar PV (Kyushu University, 2012); and 2) Floating Power Plant's Poseidon P37, with both wind and wave generation (FPP, 2019). The Kyushu device also included two turbines on a single floating foundation. There are also two instances of vertical-axis wind turbines being employed, by Gwind and Seatwirl, presenting alternatives to the market-dominant horizontal-axis wind turbine.

5.1.2 Future

5.1.2.1 Excluding early planning

If the projects examined exclude those at the planning stage, the spar concept is no longer expected to remain the market leader by 2022 (Figure 25). Instead, semi-submersible is expected to lead, with a market share of 62%, followed by spar (27%), and TLP (12%), which enjoys significantly more deployment than in the period 2008–18. It is important to note that one of the semi-submersible projects under construction – EnerOcean's 1:6 scale W2Power prototype – integrates two 100 kW turbines onto a single semi-submersible floater.

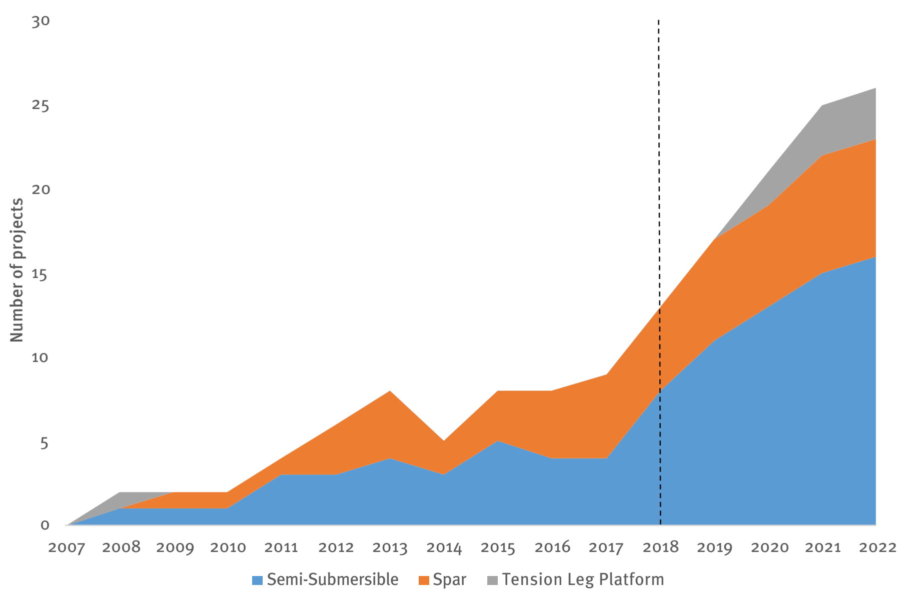


Figure 25: Cumulative number of projects by foundation design type to 2022 – excluding projects in early planning

NOTE: See earlier note about project duplication.

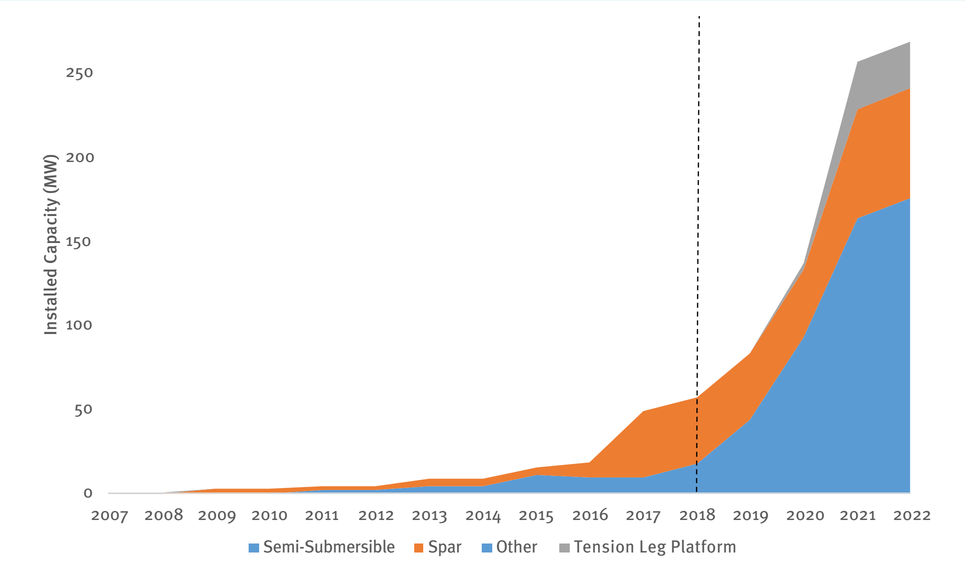


Figure 26: Cumulative installed capacity by foundation design type to 2022 – excluding projects in early planning

Spar takes an even smaller share if the market is assessed by installed capacity (Figure 26). Semi-submersible accounts for 65% of global capacity by 2025, whilst spar accounts for 24%. The reasons behind this apparent switch from spar-domination as seen in Figure 24 to semi-submersible are not examined through this study, but previous work points to a lower LCOE and simpler installation procedures (Carbon Trust, 2015).

TLP designs account for a significantly larger market share of installed capacity by 2022, standing at 10% versus negligible capacity in 2018. It is unclear why the TLP design is expected to become more popular. What is clear, however, is that the floating wind market is expected to see a growing variety of floater designs, suggesting there is unlikely to be a 'single silver bullet' configuration but, instead, a variety of different design types vying for dominance over the next 5–10 years.

5.1.2.2 Early planning

If the projects under planning are included (Figure 27), a similar spread between foundation types to 2022 is evident, with semi-submersible foundations capturing the largest market share at 80% (n=20), spar 16% (n=4) and TLP just 4% (n=1). With regards to installed capacity (Figure 28), semi-submersible dominates almost entirely, with 5.7 GW and a 98% market share. It should be noted that some of the largest semi-submersible projects integrate multiple forms of generation, most notably Denmark's Floating Power Plant design (Table 1).

The potential future market lead for semi-submersibles can be attributed to just a handful of large projects, as outlined in Section 4.2.2.2. This reinforces the view that the future of floating wind is expected to be concentrated around the deployment of semi-submersible floaters, but this is highly dependent on the design selection of just a handful of large-scale projects.

5.2 Technical design parameters

In the following analysis, we explore how the floating wind sector is 'scaling up', by examining: (1) capacity (MW) of each turbine (Figure 29); (2) hub height of turbines (Figure 30); and (3) number of turbines per project (Figure 31).

Taking projects[16] delivered since the first installation of floating wind in 2008, we find that turbine capacity has more than tripled and turbine hub height has almost doubled between 2008–13 and 2013–18.

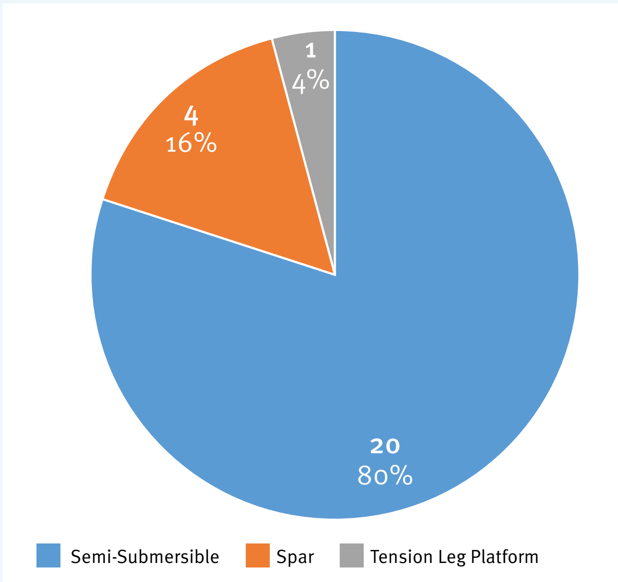


Figure 27: Number of projects by foundation design – all projects

16 We examine only projects that have either been commissioned or have a targeted commissioning date. Early planned project are shown in orange and all others in blue.

In contrast the number of floating foundations per project has stayed roughly the same, at just above a single foundation per project (Table 3). Floating wind arrays have remained a rarity, with the two-turbine 12 MW installation in Fukushima installed over 2015/16 and a five turbine 30 MW installation at Hywind Buchan Deep in 2017 the only examples to date. This trend can largely be attributed to the dominance of single-foundation pre-commercial demonstration projects to date, a necessary pre-cursor to larger scale commercial floating wind farms. Here, project developers and foundation designers typically look to scale up the size and power output of turbines first, before planning arrays. This is certainly supported by the large-scale early-stage planned projects that are over 50 MW and likely to include tens of turbines (Section 4.2.2.2). The overall picture is one of a technology that is 'scaling up', an important measure of technological maturation.

Looking forward, and considering only those projects with targeted commissioning dates, we can expect the capacity and height of turbines for floating wind projects to continue to grow. There is also expected to be growth in the number of foundations per project, with 11 projects employing more than one foundation from 2019 onwards, and seven of these incorporating four or more foundations.

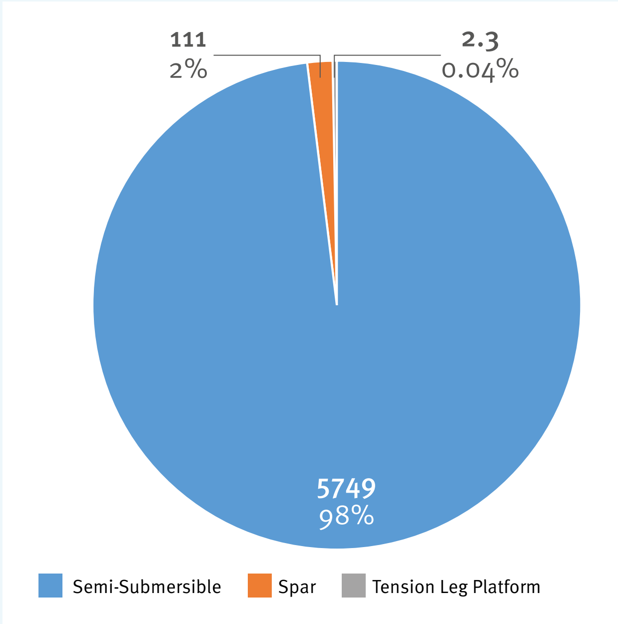


Figure 28: Installed capacity by foundation design – all projects (MW)

Table 3: Comparison of project technical characteristics between 2008–13 and 2013–18

Measure	Six year average (2008–13)	Six year average (2013–18)	Change
Turbine capacity (MW)	0.75 (n=14)	2.34 (n=13)	212%
Turbine hub height (m)	33 (n=11)	63 (n=10)	91%
Number of foundations	1 (n=14)	1.4 (n=13)	40%

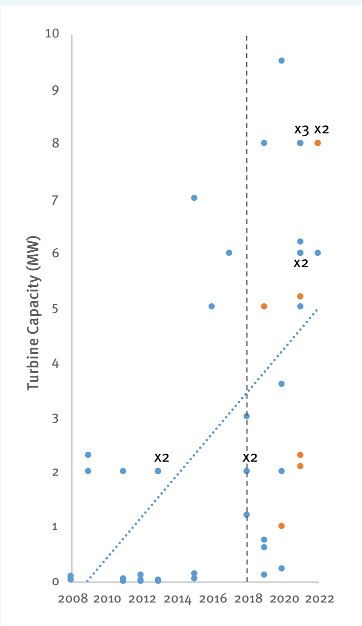


Figure 29: Floating wind projects - turbine capacity by year of commissioning

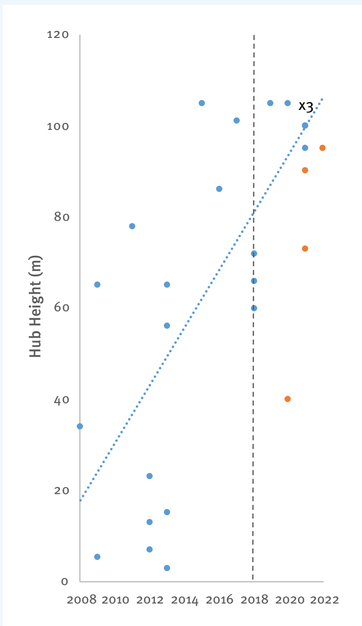


Figure 30: Floating wind projects - hub height of turbines by year of commissioning

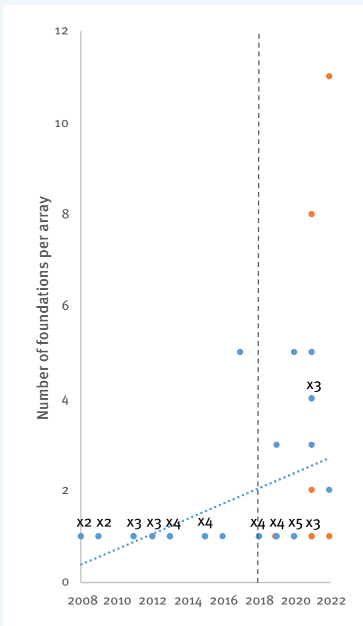


Figure 31: Floating wind projects - number of turbines per installation by year of commissioning

- Early Planning
- Commissioned, Under Construction or Post-Consent Application

Note: Projects without a targeted commissioning date are excluded. Trend line does not account for projects in the early stages of planning.

5.3 Geographical parameters

The main advantage of floating wind versus conventional bottom-fixed offshore wind is that turbines can be placed in deeper water (greater than 60 m) and further offshore. The following analysis shows the trends of average depth (Figure 32) and distance from shore (Figure 33), both present and future.

If we compare projects across two periods (2008–13 and 2013–18), we find that the average project depth remained fairly static, growing from 61 m to 65 m. Depths also rarely moved beyond approximately 100 m. Interestingly, the deepest floating wind project so far was led by Equinor in 2009, as part of their 2.3 MW Hywind demonstrator at Karmony, Norway, at 220 m deep.

From 2019 onwards, we do not expect a dramatic increase in the depths of projects, with all but one project not exceeding 120 m. Of all projects with a clear, targeted commissioning date, we find only three at or above 200 m deep. The most notable project is Equinor's 88 MW Hywind Tampen project at 240 m (Figure 32). We do find projects in much deeper waters if we consider those without a clear target date for commissioning. Most notably, there is a cluster of US projects being developed around Hawaii and off the Californian coast that range between 600 and 900 m deep (QFWE, 2018).

Stronger progress has been made over distance from shore in recent years, with the average between the two periods almost doubling from 5 km to 11 km. Distances from the shore have not yet exceeded Equinor's Buchan Deep at 25 km, although together there have been six projects at or above 20 km since 2008. The majority of the other projects are at a distance of 10 km or less.

For the foreseeable future, we are likely to see the average distance to shore grow, as a larger number of projects are deployed at between 10 and 20 km. Again, the outlier is Equinor's Hywind Tampen 88 MW project in Norway due for 2022 which will be situated 125 km offshore. Taking a longer time horizon, there are a number of early-stage planned projects with commissioning dates, especially in the US, France and Japan, that move beyond 20 km offshore, but none is as far out as Hywind's Tampen.

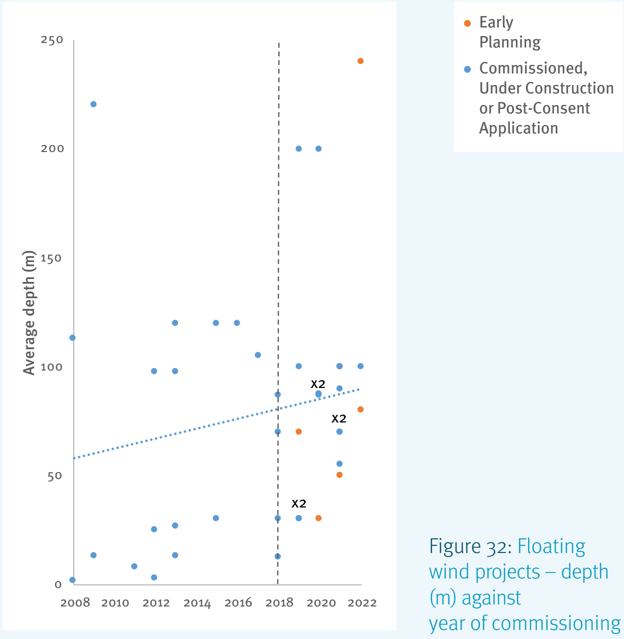


Figure 32: Floating wind projects – depth (m) against year of commissioning

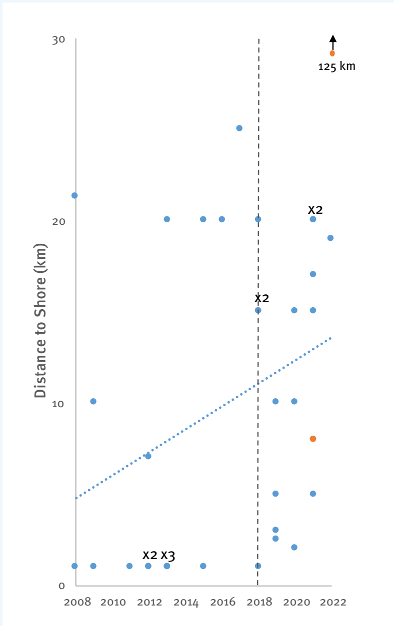


Figure 33: Floating wind projects – distance to shore (km) against year of commissioning

Note: Projects without a targeted commissioning date are excluded. Trend line does not account for projects in the early stages of planning.

Table 4: Comparison of floating wind project technical characteristics between 2008–13 and 2013–18

Measure	Six year average (2008–13)	Six year average (2013–18)	Change
Depth (m)	61 (n=13)	65 (n=11)	7%
Distance (km)	5 (n=13)	11 (n=11)	120%

Taken together, our analysis points to how floating wind projects are on average operating in waters deeper than most bottom-fixed foundations are economically capable of (i.e. greater than 60 m) and at distances beyond 10 km offshore. Looking forward, projects are expected to push gradually into deeper and more remote waters, albeit without any major step-change in depth or distance. On the one hand, this trend might be a function of technological progress, with innovation enabling generation in deeper, more remote waters. However, pushing into such waters on a commercial basis must ultimately balance the benefits of capturing a richer wind resource with the additional costs incurred, such as additional cabling or foundation materials. Consequently, a 'sweet spot' of both distance and depth will likely be found at which floating wind proves the most economical.

6

Discussion

6.1 Sectoral trends

6.1.1 Market growth – past and future

Since 2008, the sector has enjoyed growth, progressing from almost no installed capacity to 57 MW across 12 projects in 2018. There is also a healthy pipeline of 11 floating wind projects at an advanced stage of planning (i.e. at least applied for consent) and planned for commissioning by 2022. Together, these would account for 268 MW, almost five times that of today. Looking further out, an additional 24 projects are at a very early stage of planning and would deliver up to an additional 5.9 GW of installed capacity.

So in total how much capacity might be delivered by 2030? We offer a simplistic and empirically grounded approach, which is based on historical deployment of planned offshore wind projects in the UK. First, whilst it is difficult to say when the early-stage planned projects will be commissioned, we assume that they all target commissioning before 2030. Second, to understand what proportion of these projects will progress to commissioning, we examine the RenewableUK Project Intelligence database. It shows that, of the 59 UK offshore wind projects[17] that have already been commissioned or cancelled, approximately 17% never applied for consent, 8% applied but were refused or withdrew during the process, and 5% were granted consent but ultimately cancelled. Consequently, around 69% of offshore wind projects progressed from the planning stage to commissioning. Applying this success rate to the total 5.9 GW of planned capacity, either pre- or post-consent, we might expect approximately 4 GW of capacity to become commissioned globally over the next 10–15 years. This is in addition to the 247 MW of capacity that is either operational, under construction or likely to become successfully consented,[18] giving us a total estimated capacity of 4.3 GW by 2030 (Figure 34). Whilst this estimate is considerably less than Equinor's projection of approximately 12 GW by 2030 (Equinor, 2019b), it is closely aligned with the ORE Catapult's estimate of 4 GW by 2030 (ORE Catapult, 2018).

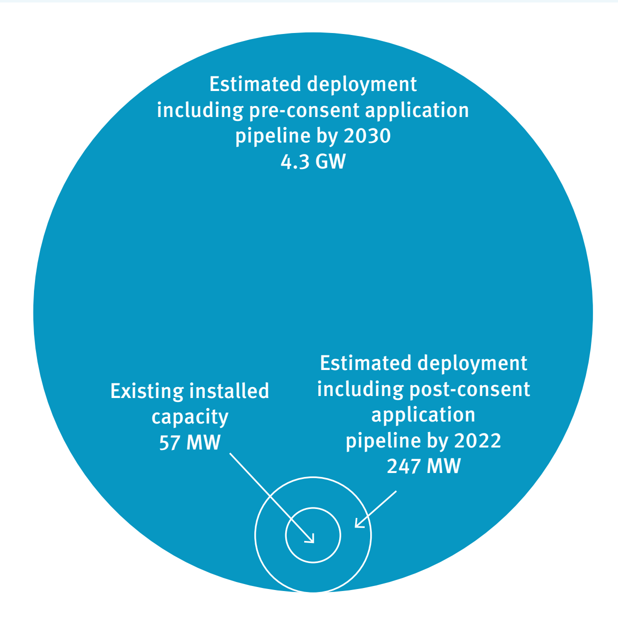


Figure 34: Estimated potential deployment of floating wind pipeline

It is also interesting to note that, during a similar 12-year time period, bottom-fixed offshore wind grew from 67 MW in 2000 to 5.3 GW by 2012 (IRENA, 2018, 2019c); a growth trajectory that is startlingly similar to our 2030 estimate for floating wind. Furthermore, bottom-fixed offshore wind in 2000 was arguably a similarly unfamiliar proposition to floating wind today. This provides some confidence that our 2030 growth trajectory is grounded in past performance.

This estimate should however be accompanied with a number of important caveats. The first is that our estimate is drawn from a project pipeline that is disproportionately reliant on just a handful of large-scale projects (Table 1), meaning the cancellation of just one project would have a dramatic impact on this estimate. The others relate to basing the project conversion rate on historical UK offshore wind planning data. For instance, the project data is for traditional bottom-fixed offshore wind, not floating wind. This raises questions about whether floating wind can emulate traditional offshore wind's success rate, despite it being a much-less-familiar proposition, thus carrying with it more risk.

The second caveat is that the conversion rate is based on UK planning data only and is not representative of the global market, where projects may have a better or poorer record of moving from planning to commissioning. To address this, access to global offshore wind planning consent data is required. For a more accurate estimate of future growth, robust modelling work is required that accounts for wider supply chain, environmental, political, economic and technological factors, as discussed in Section 7.

6.1.2 Leaders by deployment

Japan has the largest number of projects at five. However, the UK leads in terms of installed capacity, with 32 MW and a 56% market share. Japan ranks second with 19 MW and a 33%

17 The UK was selected, as complete data is provided for whether projects applied for consent or not. Data correct as of 11 February 2019. We exclude projects that have yet to apply for consent or have yet to conclude the consenting process. We identified an additional 15 projects that have already been consented but these are excluded from the analysis as we are unclear what proportion of these will ultimately be commissioned.

18 Here, we initially take the 57 MW of operational capacity, plus 30 MW under construction. This is added to the 184 MW of capacity that has at least applied for consent, of which we assume 13% will not ultimately reach commissioning, as explained in the main text, leaving 160 MW. This provides a total of 247 MW. It also assumes that only one project, the 2 MW Kincardine A turbine, will be decommissioned by 2030. In reality more projects will be likely to be decommissioned for various reasons (e.g. technical failures).

Table 5: Current and future installed capacity by country of deployment compared with attractiveness to renewable investment (Source: adapted from Ernst and Young 2018)

Country	Pre-consented projects (MW)	2022 pipeline: construction, consented or applied for consent) (MW)	Installed capacity 2018 (MW)	Offshore wind (index)	Offshore rank	Renewable Energy Country Attractiveness Index score (index)	Rank
USA	2150	12	0.1	53	(3)	63.8	(2)
UK	1938	78	32	57	(1)	57	(8)
Japan	1027	19	19	44	(8)	44	(7)
France	510	100	3.2	51	(4)	51	(5)
Portugal	125	25	0	25	(18)	52.3	(25)
Spain	21	27	0	26	(15)	54.7	(17)
South Korea	0	0.8	0	26	(16)	51	(31)
Sweden	0	0.03	0.03	27	(13)	50	(32)

share, with most remaining capacity residing in France (3.2 MW) and Norway (2.3 MW). It is also observed that some 'first-movers' in floating-wind deployment, such as Denmark and Italy, have subsequently stepped back from the market, not installing any new projects over the past few years.

Focusing on the 268 MW pipeline of projects that have at least applied for consent to be commissioned by 2022, we find that most of this will be deployed in France (100 MW) and the UK (78 MW), with significant capacity also delivered by Spain (27 MW), Portugal (25 MW), Japan (19 MW) and the USA (12 MW). Interestingly, many of these countries, such as Portugal, Spain and the US, had no or negligible installed capacity by 2018, pointing to how competition in the floating wind market is expected to grow and its geographical base to broaden. The sector is expected to grow its experience of deployment in a broader range of environments and broaden its supply chain internationally.

Broadening the analysis out to earlier-stage planning projects, it is the USA (2.2 GW) and UK (1.9 GW) that dominate future deployment. Together, they account for roughly half of all new projects, and over two thirds of new capacity, with Japan (1 GW) and France (0.5 GW) also planning substantial deployment. Whilst the UK's move builds upon its existing market lead in both conventional and floating offshore wind, the USA's strong pipeline is surprising, given its relative lack of offshore wind to date, with just 30 MW of capacity in 2018 (GWEC, 2019). However, the US Department of Energy highlights that, as of 2018, the USA has 25.5 GW of all forms of offshore wind in the pipeline, with 2 GW of this expected to be operational by 2023 (Spitsen et al., 2018). Therefore the USA's move into floating wind might be viewed as part of a broader offshore wind growth strategy.

6.1.2.1 Drivers for deployment

Whilst this report has not sought to understand the underlying factors responsible for floating wind's growth, an important question remains: why is past and future deployment of floating wind concentrated in a handful of countries? One explanation might be the strong correlation between those countries with a strong floating wind pipeline and where there is already an attractive investment environment for offshore wind. Comparing our results with Ernst and Young's Renewable Energy Country Attractiveness Index (RECAI)[19] (EY, 2018) highlights how the countries with strongest floating wind pipelines are also typically those that are most attractive to investors in offshore wind and renewables more broadly. For example, the countries with the largest early-stage project pipelines (i.e. the USA, UK, Japan and France), all rank in the top ten countries in terms of market attractiveness for both offshore wind and renewables (Table 5).

Focusing specifically on the USA, given its impressive pipeline of 2.2 GW, the US Department of Energy points to how this drive is primarily underpinned by federal policy making, namely dedicated state-level procurement and offtake mechanisms (US Department of Energy, 2018a). Furthermore, 30 US states have renewable portfolio standards, which establish mandatory goals for utilities regarding renewable energies (Marcos Suárez, 2018). In contrast, the Trump administration has withdrawn from the Paris Agreement on Climate Change and moved to promote its fossil fuel industry, such as through expediting federal leases for drilling oil and gas on public land (Fears, 2018). The picture is one where (floating) offshore wind deployment is being primarily driven by federal, rather than national, policy making. The UK's own situation is considered in detail in Section 7.

19 EY's index for technology-specific country attractiveness takes into account natural resource, power offtake attractiveness, political support, technology maturity and forecasted growth. We note that the index also accounts for the size of the future project pipeline, but we are unable to disaggregate this from the rest of the index (EY, 2019).

It is also important to consider geographical factors. For example, the USA, UK and Japan are all home to a rich deep-water wind resource, considered too deep for conventional fixed-bottom foundations (Section 1). It is therefore natural for these countries to be looking to take advantage of floating wind, given the characteristics of their wind resource.

6.1.3 Leaders by design

To date, Norway has led in terms of foundation design and development, accounting for 57% of installed capacity by 2018, with Japan (28%) and France (11%) also accounting for significant shares. If we include all projects that have at least applied for consent, the balance shifts, with the USA taking the lead (41%), followed by France (21%) and Norway (12%). Looking further into the future, and at projects at a much earlier stage of planning, the USA retains the lead, with 2.3 GW (39%), again followed by France with 2 GW (34%). Interestingly, there are some countries with a strong pipeline for foundation design but who are weak on deployment, such as Denmark, whilst others are the opposite, such as the UK (see Section 7).

6.1.3.1 SMEs and incumbent firms

As might be expected from an emergent industry such as floating wind, many of the companies involved in the design and development of floating foundation concepts are SMEs. Key players include the USA's Principle Power, which has already deployed[20] 27 MW and France's Ideol with 5 MW of projects. There are also numerous other SMEs with floaters at an earlier stage of development but with grand ambitions, including Denmark's wind and wave power-generating Floating Power Plant, with 424 MW of projects planned. What is interesting, however, is the large number of incumbent multi-national firms engaging with the sector across three main groups: (1) oil and gas majors; (2) energy utilities; and (3) original equipment manufacturers (OEMs).

The current market leader is Equinor, formerly known as Statoil, which remains heavily involved in oil and gas. For example, in 2018 it was the 11th most valuable oil and gas operations company in the world, with a valuation of $77.6bn (Forbes, 2019). Equinor's move into floating offshore wind has been mirrored by Shell, the world's second most valuable oil and gas company. It has invested in Stiesdal's TetraSpar demonstration project, due for commissioning in 2020, increasing its share in the project to 66% in 2019 (Wind Power Offshore, 2019). It has also invested in Makani, which will shortly be deploying its airborne wind energy kite system offshore (Felker, 2019). The major Spanish oil and gas company Repsol has also followed suit, becoming a 19% shareholder in the WindPlus subsidiary, set up to deliver the 25 MW WindFloat Atlantic project off the west coast of Portugal (EIB, 2018)(Section 4.2.2.2 and Table 1).

These moves might be viewed as part of a wider strategic shift from the oil and gas industry into the energy sector, with some targeted investment in renewable energy companies (Annex, 2018; Shaw, 2018). This raises an important question about why leading profitable oil and gas companies are turning to innovative renewable energy technologies. Given their rich history of overseeing the installation and operation of offshore sub-structures and their long-standing connections with the offshore oil and gas supply chain, they may offer a natural fit as floating offshore wind developers. This view is echoed by Equinor:

> *'Floating wind can be the next wave in renewable energy – and we're uniquely positioned to play a major role in this industry. For us, offshore wind was a natural move, and an opportunity to capture the synergies we see between our renewables and oil and gas activities'*
>
> (Equinor, 2019a)

On the one hand, the oil and gas majors' move towards floating wind signals a change in their traditional business model, which has not normally focused on renewable power generation. On the other, one could argue that floating wind supports business as usual. For example, Equinor's planned 88 MW Tampen array next to the five Snorre A and B and Gullfaks A, B and C platforms off Norway would provide 35% of their annual power demand. Floating wind power would support extraction operations by displacing the need to burn fossil fuels to power further extraction. This, therefore, saves a valuable market commodity for general sale. Furthermore, the approach can reduce the carbon emissions and environmental impact of extraction, thus helping to satisfy regulatory obligations and corporate social responsibility goals.

Another important class of incumbent are the energy utilities, some of whom have also moved into the floating wind market. Major French utility Engie is also involved in the WindFloat Atlantic project in Portugal and is part owner of the 24 MW EFGL project in France (Engie, 2019). EDF also wholly own the planned 24 MW Provence Grand Large project. Innogy, a subsidiary of German RWE nPower, also purchased a third share in the TetraSpar project in 2018 (Wind Power Offshore, 2019). At an earlier stage, Iberdrola, the world's fifth most valuable electricity utility, has invested in the development of the TLPWind design (Iberdrola, 2014), although it is unclear whether it has continued with its development in recent years.

20 Decommissioned, operational or under construction.

OEMs represent another important group of incumbents which have entered the market, primarily for technology design, including DCNS's Sea Reed foundation design and ACS Group's Cobra concept. OEMs have also invested in project development, for example Siemens Gamesa involvement in the Floatgen consortium to test Ideol's 2 MW floating turbine. The Fukushima FORWARD consortium (Section 4.2.2.2 and Table 1) also includes various high-profile OEMs like Mitsubishi and Hitachi.

Whilst the political and economic capital derived from multi-national investment can play a key role in accelerating technology innovation and market formation (see Yin, Ansari and Akhtar, 2018), it can generate pressure on the technology to commercialise rapidly. Parallels can be drawn with the case of wave power developers (Hannon, Van Diemen and Skea, 2017), who also moved to take advantage of investment from incumbents but were then faced with premature pressure to commercialise before the underpinning technology was ready. Consequently, mistakes were made and the technology's progress was slower than investors had expected. This had devastating effects on the technology's perceived legitimacy, in turn diminishing the public and private sectors' appetite to invest.

Unlike wave power, floating wind is being operated at a larger scale and is building on a now well-established offshore wind supply chain and leveraging mature technologies (e.g. turbines). Even so, with planned projects beyond 1 GW scale (Table 1), the sector has extremely ambitious plans to grow within a relatively short time span, some of which are led by incumbent firms. The availability of public demonstration funding, pre-commercial revenue payments or government back finance (Section 8.1) will offer more patient capital and help the sector avoid going 'too big, too soon'.

6.2 Technological progress

6.2.1 Leading foundation design

Today, the spar floater is the most common foundation design in terms of installed capacity. However, this dominance is expected to be short lived, with the semi-submersible set to become the most common deployed type of foundation, with 65% of installed capacity[21] by 2022. Across the medium term, we also note that projects utilising TLP designs become more common, accounting for 10% of installed capacity by 2022. Looking further ahead, semi-submersible foundations account for almost all early-stage planned projects at 98% of the 5.9 GW of planned installed capacity. Much of this installed capacity incorporates mixed forms of generation, such as Floating Power Plant's wind and wave device.

This report has not sought to understand the reasons behind the shifting market dominance of different designs. However, what is clear from Section 2 is that different floating designs offer contrasting strengths and weaknesses. Taking the two most popular designs to date, we find that the low-draft of semi-submersible foundation means that it can operate in relatively shallow waters and can be assembled onshore and tugged to site, making it less dependent on port infrastructure and supply-chain services. However, it presents a more complicated manufacturing process, due to its complex design and is often very demanding of raw materials. In contrast, spar designs typically require offshore assembly and the associated equipment (e.g. dynamic positioning vessels) and are best suited to waters greater than 100 m in depth. However, they are typically less complex to manufacture, due to their relatively simple design.

This illustrates how the choice of foundation design for future projects is likely to be determined on a case-by-case basis, with one design typically better suited to a project's characteristics than another. These may relate to the physical characteristics of the site, such as water depth, or infrastructural or supply-chain issues such as the availability of port infrastructure or fabrication services. Instead of a single 'optimum' design becoming dominant, we expect to see a marketplace emerge with a range of different foundation designs, each associated with a specific set of project characteristics.

6.2.2 Technological scale

Our research, therefore, finds that floating wind technology is steadily maturing and moving closer to commercial scale. Excellent progress has already been made in terms of turbine height and power output. We find that turbine capacity has more than tripled and turbine hub height has almost doubled between 2008–13 and 2013–18. Projects planned for the late 2010s and 2020s also indicate a continuation of this scaling up. For example, the second phase of Kincardine in the UK is planned to include five 9.5 MW turbines – significantly larger than the 6 MW turbines installed at Hywind Buchan Deep.

In contrast, almost all projects have involved single turbine demonstration instead of deployment of multi-turbine commercial arrays between 2008 and 2018, pointing to the pre-commercial nature of the technology at present. Even so, the commissioning of Equinor's five turbine array at Buchan Deep in 2017 is potentially the first of many arrays, with the three-foundation Windfloat Atlantic under construction and seven other multi-foundation projects that have either applied for or been granted consent.

21 Excludes early-stage planned projects.

6.2.3 Depth and distance from shore

Over the past ten years, there has been a trend for floating wind projects to move further offshore, with the average distance roughly doubling from 5 km to 11 km between 2008–13 and 2013–18, with the farthest project – again, Equinor's Hywind project at Buchan Deep – reaching a distance of 25 km from shore. Projects have not made the same progress in terms of water depth, with the average depth across the two periods remaining fairly static (61 m versus 65 m).

The reason for the discrepancy between projects moving farther offshore but remaining at similar depths is not clear. One potential reason is that many demonstration projects have taken place near harbours or offshore energy test centres that are relatively close to shore but with reasonable water depths. This is in the context of, at a pre-commercial stage, project developers' focus being predominantly on scaling up the technology in terms of size and capacity (Section 6.2.2). Thus, in order to offset some of the inherent risk of scaling-up the technology, developers sought to operate at modest depths (approximately 30 m) but in near-shore locations (up to 1 km). However, as the technology has matured and developers have grown in confidence, projects have been located in waters much farther offshore, often 20 km or more, but at depths rarely exceeding 120 m.

Looking further ahead, there is a medium-to-long-term trend for planned projects to move into deeper, more remote waters, with some early stage projects moving into waters up to 900 m deep and over 125 km offshore. Again the reason for this is not entirely clear. One might expect that this is due to a dwindling number of appropriate sites that possess both an attractive wind resource and are located in relatively shallow, near shore waters. Further assessment is required to test this hypothesis.

Another factor is how offshore wind has been identified as a potentially important means of reducing the carbon emissions and environmental impact of oil and gas operations (Korpås et al., 2012). See, for example, Equinor's planned Tampen project in Section 6.1.3.1, which would be located approximately 125 km offshore and in water 240 m deep, making it the deepest and most remote planned project that is expected to be delivered by 2022. If floating wind becomes a preferred option to power offshore oil and gas operations in wind-rich areas, then we may see a push into deeper, more remote waters.

7

Recommendations for future research

Building upon this report's examination of the floating wind market's recent and emerging trends, future research would helpfully cover the following areas:

Modelling growth of floating wind market

Accurate estimates of the floating wind market's future size and composition will require robust modelling that accounts for a wide range of factors, including, amongst others:

(1) technological limitations of existing floating wind (e.g. depth, ocean conditions etc.) and supporting technology (e.g. sub-sea cabling to distant sites);

(2) the availability of appropriate sites and their proximity to centres of power demand;

(3) expected cost reductions of floating wind and rival energy technologies;

(4) policy and regulatory drivers/barriers; and

(5) supply-chain capacity.

Costs of floating wind

There is a need for an international assessment of existing project-LCOE for floating wind projects, which has been peer-reviewed and is publicly available.[22] Such analysis should offer a breakdown of how the different products and services that make up a floating wind project contribute to the overall LCOE. An assessment of how these costs have changed over time and which project characteristics (e.g. turbine capacity, number of turbines, water depth, distance from shore and foundation type) or market factors (e.g. supply chain) might be responsible is also required. The International Renewable Energy Agency (IRENA) is well placed to help deliver on much of this work by expanding the scope of its Renewable Power Generation Costs report to include floating wind.

Domestic content of existing projects and opportunities for growth

International analysis of countries' domestic content of their floating wind projects, using the methodology developed by BVG Associates (2015a). This will help to identify the countries that have performed best in terms of maximising their domestic content, offering potential lessons to other countries (e.g. the UK) about how to maximise their own. In parallel, research is needed into what new supply-chain products/services opportunities the floating wind sector presents[23] and thus, where countries may need to bolster capacity to support market growth.

Assessment of public and private investment

By utilising project data and industry databases such as Bloomberg New Energy Finance, it is important to consider the mix of public and private sector investment that has been required to deliver floating wind projects to date. This would consider the full spectrum of investment, including capital grants, loans, equity financing, revenue payments, etc. These insights will help explain why some countries have been more successful at promoting floating wind deployment (e.g. UK, Japan) than others. Close examination of the relative effectiveness of government policy mechanisms that have been employed in different countries would be very helpful.

22 We note that Quest FEW provides an assessment of floating wind project costs. However, this is available only to paying subscribers.

23 For example, compared with traditional offshore wind technology, floating wind offers more offshore mating, anchors and mooring lines, as well as the 'unhook and tow back to shore' technique for major maintenance.

8

UK policy recommendations

This report provides a special emphasis on floating wind in the UK and Scotland and below we present policy recommendations to help accelerate growth in this sector.

8.1 Innovation support

Through its Offshore Wind Sector Deal (BEIS, 2019b), the UK Government has committed to support floating wind technology, with a similarly supportive stance from the Scottish Government (2017). We therefore consider the appropriateness of the support mechanisms currently in place. Looking beyond earlier stage R&D support, which is covered elsewhere (Carbon Trust & ORE Catapult, 2017), we note two important weaknesses in the UK's innovation support framework for floating wind projects at or beyond the part-scale ocean demonstration stage: (1) the over-reliance on fragile EU innovation support; and (2) the lack of pre-commercial revenue payments.

8.1.1 Over-reliance on fragile EU funding

Both grant funding and government-backed finance are critical forms of funding to support energy technology innovation. The former typically focused on support for part- or full-scale technology demonstration, whilst the latter tends to be provided to larger-scale projects that are closer to commercialisation. Looking across UK and EU programmes, we find that UK floating wind projects are eligible for significant EU funding, which may no longer be available post-Brexit.

8.1.1.1 Grants

The UK's two main channels for pre-commercial energy demonstration funding are the UK Research and Innovation (UKRI)'s Industrial Strategy Challenge Fund (ISCF) and InnovateUK's Energy Catalyst. Whilst the ISCF represents a significant investment, it has to date focused on funding smart, local energy systems via its Prospering from the Energy Revolution programme. We also note that the Energy Technologies Institute (ETI), which has a history of funding large-scale demonstration offshore energy projects, is due to close in 2019. The ETI was due to provide £25m to the Pelastar floating demonstrator, but the project was cancelled (Carbon Trust, 2015). Devolved administrations also have their own schemes such as the Scottish Government's Scottish Low Carbon Infrastructure Transition Programme (LCITP),[24] which has recently offered support of up to £10m per project (Scottish Government, 2019).

The EU Innovation Fund, under its predecessor NER300, provided €30m to support the 25 MW Windfloat Atlantic project, which is currently under construction (European Commission, 2017). Horizon2020, on the other hand, has supported the DemoWind programme, established to demonstrate technologies capable of driving down the cost of wind. Its predecessor, the EU Framework Programme (FP7), provided almost €20m to the 2 MW Floatgen demonstrator (Cordis, 2014).

8.1.1.2 Government-backed finance

With the privatisation of the Green Investment Bank in 2017, there is generally a lack of publicly backed finance schemes to support technologies such as floating wind. Finance is available in the UK through schemes such as the UK's £20m Clean Growth Fund (BEIS, 2019a) and the Scottish Government's £20m Energy Investment Fund (Scottish Enterprise, 2019). It also remains to be seen whether Scotland's Scottish National Investment Bank, planned for 2020, will offer investment into technologies such as floating wind.

The most significant scheme available to UK energy projects at present is the European Investment Bank's InnovFin Energy Demo programme,[25] which provides loans, loan guarantees or equity-type products to projects deemed too risky to access other sources of funding on affordable terms (EIB, 2014). It typically offers finance of between €7.5m and €75m to innovative energy demonstration projects (EIB, 2019a). For example, it provided a €60m loan to the 25 MW Windfloat Atlantic project (European Commission, 2018). Finally, demonstration funding has also been available through the European Regional Development Fund, via bodies such as the Welsh European Funding Office or Scotland's LCITP.

8.1.1.3 Analysis of support

Our analysis did not identify any recent investment from the UK Government or devolved administrations into full-scale demonstration of floating offshore wind projects. In contrast, EU programmes have supported large-scale projects, albeit outside of the UK. Consequently, whilst EU funds have not been forthcoming for the UK, evidence suggests that floating wind is a priority for EU innovation support. With Brexit, and the UK's expected departure from the EU in late 2019, it is still unclear to what extent the UK will be able to access any of these EU sources of grant or finance support. Floating wind projects therefore run a serious risk of being unable to secure substantial public funding in a post-Brexit world (Figure 35).

24 This is part-funded by the EU's European Regional Development Fund.

25 'The EIB is active both inside and outside the European Union. [However,] the majority of EIB lending is attributed to promoters in the EU countries (about 90 percent of the total volume) supporting the continued development and integration of the Union.' (EIB, 2019b)

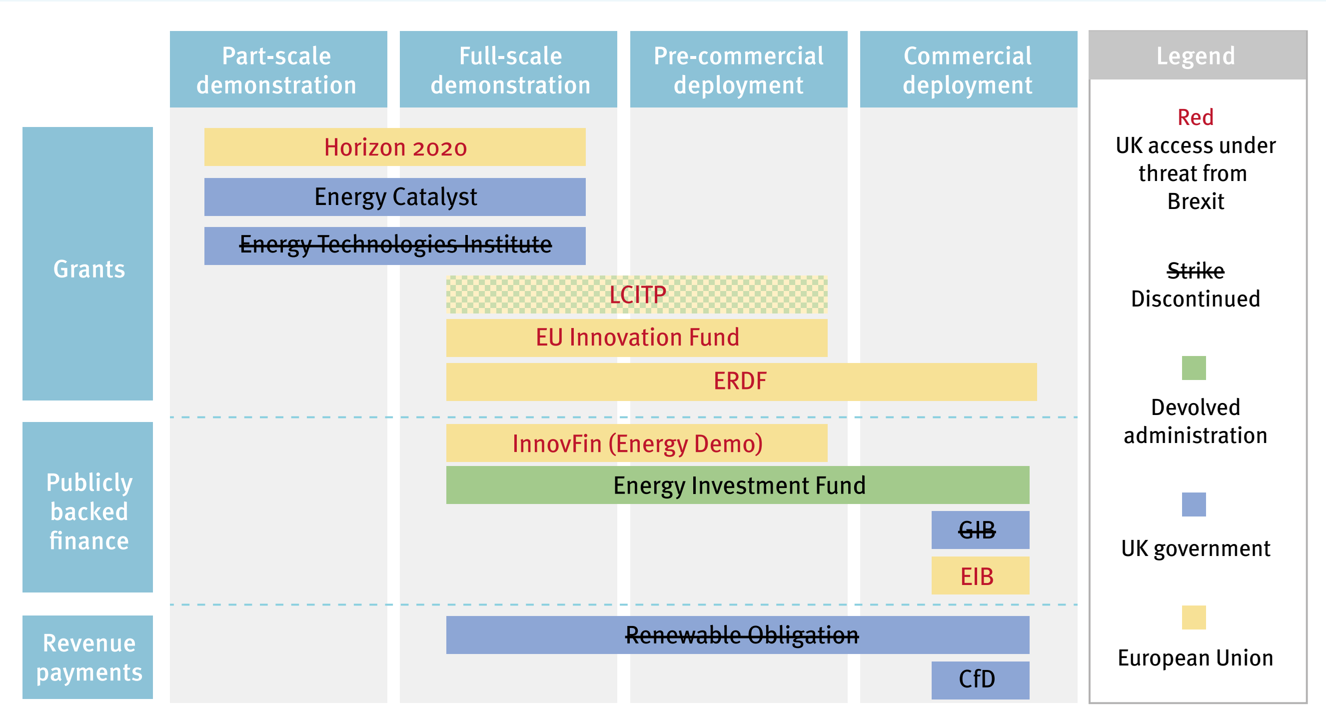


Figure 35: Major funding programmes offering innovation support to floating wind projects in the UK

NOTE: LCITP - Low Carbon Infrastructure Transition Programme; ERDF - European Regional Development Fund; GIB - Green Investment Bank; EIB - European Investment Bank; CfD - Contracts for Difference

Policy recommendation 1

It remains uncertain whether the UK will be able to access EU funding for large-scale energy technology demonstration post-Brexit. With the absence of any UK funding covering this shortfall, floating wind could face a significant shortfall in public investment.

The **UK Government (and devolved administrations) should first move to retain access to EU demonstration funding post-Brexit. If this proves unsuccessful, the UK must then consider how it can use its own public funds to cover any prospective shortfall, with a focus both on demonstration grants and government-backed finance**. In particular, demonstration funding could usefully be ring-fenced through a second phase of the UKRI's ISCF, with an explicit focus on offshore renewable demonstration.

8.1.2 Lack of pre-commercial revenue payments

Long-term revenue payments are generally considered an important 'market-pull' mechanism[26] to help grow new energy generation technology markets. Until recently, pre-commercial and commercial UK floating wind projects were able to access the Renewable Obligation (RO). It provided eligible renewable generators with support per MWh of renewable electricity generated at a fixed rate for 20 years.[27] In Scotland, special provision was made for floating wind, which received 3.5 ROCs per MWh (Ofgem, 2018a). Both the UK's operational floating wind projects – Hywind Buchan Deep and Kincardine – currently benefit from this scheme. For example, taking the period from 1 Dec 2017 to 30 November 2018, we estimate that Equinor received £25m from the RO during this period.[28]

In October 2018, the RO closed to any new floating wind generation, meaning this valuable source of pre-commercial support was no longer available. Prior to the announcement,

26 These policies create a demand for a new type of product or service, in turn 'pulling' technologies through the innovation chain towards commercial deployment.

27 Electricity suppliers were required to source a portion of their electricity from low-carbon sources and could purchase renewables obligation certificates (ROCs) from generators to help them meet their obligations. Suppliers failing to meet their obligations had to pay the buyout price for every MWh they supplied without the necessary certification.

28 Data was taken from Ofgem's Renewables and CHP Register. The number of ROCs is calculated by the number of Renewable Energy Guarantees of Origin (REGOs), multiplied by the 3.5 ROCs per MWh for floating wind. Assumes a buy-out price of £45.58 for 2017/18 and £47.22 for 2018/19 (Ofgem, 2018b) per ROC, each period running from 1 April to 31 March. A recycle value of £5.85 per ROC is taken for both the 2017/18 and 2018/19 period (Ofgem, 2018c). Recycle value for 2018/19 not available at time of calculation so we have adopted the previous year's, which is likely to be marginally lower than the actual value, potentially under-estimating the total subsidy Equinor received. Our independent analysis, which accounts for a typical wind resource year and Equinor's own capacity factor for Hywind Buchan Deep, yields a very similar amount of subsidy, suggesting this level of subsidy is likely to be normal over forthcoming years. Equinor declined to confirm the exact sum they received via the RO for Buchan Deep.

the floating wind industry encouraged government to extend the deadline to April 2020 (Foxwell, 2018), claiming two further consented schemes, namely the 10 MW Dounreay Tri and 12 MW ForthWind, would be unlikely to go ahead without the subsidy (Ward, 2018). The extension was not granted and today the future of both these projects remains in doubt (4COffshore, 2018a).

Floating wind has now been left with the Contracts for Difference (CfD) as the only scheme that can subsidise its power generation. Here, floating wind must compete for the second 'less-established technologies' pot[29] against other emerging renewable energy technologies on cost, including traditional offshore wind. Looking towards the third CfD round and the delivery period 2023–25, which opened on 29 May 2019, the administrative strike price for offshore wind has been set at £53–56 per MWh (2012 prices). This is effectively 'the maximum strike price a project of a particular technology type in a given delivery year can receive during an allocation round' (BEIS, 2018). It is highly unlikely that a floating wind project will secure CfD support during the third round competing at these prices, with the actual LCOE of floating wind in 2018 estimated to be £160–177 MWh for pre-commercial projects (WindEurope, 2018). Consequently, this raises serious doubts about floating wind being able to out-compete traditional offshore wind on price alone and secure CfD subsidy in the near future – a vital route to market.

One recent study has proposed two new policies to support pre-commercial energy technology projects and fill the gap left behind by the RO. These are an Innovation Power Purchase Agreement (IPPA) for installations below 5 MW and Innovation CfD (iCfD) for projects between 5 and 100 MW (Scottish Renewables, 2019). In effect the iCfD represents a separate pot for more expensive emergent energy technologies, such as floating wind, tidal stream, wave power etc., offering strike prices above £150/MWh. Whilst the IPPA may still be appropriate for single floating foundation installations, using turbines with a combined capacity below 5 MW, the commissioning of the 30 MW Hywind array in Scotland indicates that the technology is capable of larger-scale application and could fit better within the remit of the iCfD. It represents a potentially important way forward to help grow the UK's floating wind market and other nascent offshore renewables.

Policy recommendation 2

With the RO no longer open to new generation and the CfD designed to favour least-cost technologies, floating wind faces the very real prospect of being unable to secure any long-term revenue-based subsidy for the foreseeable future. The UK's two floating wind projects have been subsidised by the RO, and its removal has delayed two already consented projects indefinitely.

A new subsidy is therefore needed if further pre-commercial floating wind projects are to be deployed in the UK. One option would be to create an innovation-oriented CfD pot, which would allow for more expensive pre-commercial technologies (e.g. floating wind, tidal stream) to compete against one another for a guaranteed strike-price. Insulating floating wind from competition with more mature technologies, such as bottom-mounted offshore wind, would create a more level playing field and a route to market.

Looking beyond the UK, we find that there are a number of past or future projects focused on niche market application. For example, Equinor's Hywind Tampen project will provide power for extraction at two oil and gas fields in the North Sea (Section 6.2.3). Another is island installations, such as the large-scale planned projects in Hawaii and Japanese deployments such as Kabashima in the far south west.

Floating wind potentially has something to offer both markets, either by displacing valuable hydrocarbons to fuel extraction of fossil fuels or by undercutting the high electricity costs normally faced by island communities in importing power from the mainland.

The UK is home to both types of niche markets, with numerous island communities and a sizeable offshore oil and gas sector. In the absence of pre-commercial subsidy, it may be necessary for project developers to service niche markets[31] via some form of power purchase agreement, in order to ensure the project is profitable and, more broadly, to drive down costs through economies of scale.

Policy recommendation 3

Floating wind in the UK could usefully focus on niche markets where customers typically pay a premium for electricity and there is the potential for floating wind to operate on a more 'level playing field'. **Government could usefully fund a study to identify potential niche markets in the UK for floating wind, alongside the associated cost benefits and barriers to deployment**. Insights would inform the design of any targeted support to help facilitate access to these markets.

29 An analogous term is beachhead market, a 'place where, once you gain a dominant market share, you will have the strength to attack adjacent markets with different opportunities' (Aulet, 2013).

8.2 Supply chain

8.2.1 UK content

In 2017, the UK had achieved almost 48% content[30] of its offshore wind farms, up from 43% in 2015. UK content in these projects was strongest across development and operational expenditure, but much weaker for capital expenditure. Following the release of the UK's offshore wind sector plan, we find that the UK Government targets UK content to grow to 60% by 2030, largely concentrating on increases in the capital expenditure phase (BEIS, 2019b), including turbines, foundations, etc.

The ORE Catapult estimate that, in an ambitious scenario, if 2 GW of floating wind projects could be commissioned by 2030 and there were the necessary strategic public and private investments in key elements of the supply chain (e.g. ports and fabrication), the maximum potential for UK content is 57% of the lifetime supply chain of floating wind projects by 2031 (ORE Catapult, 2018), including 41% of CAPEX. However, without such strategic investment, content could fall as low as 20%, with just 11% of CAPEX. The message is, therefore, that, with the right type of support, floating wind could help the UK to meet its 2030 60% content target.

Whilst our research has not calculated the exact the UK economic content of the UK's two floating wind projects installed in Scottish waters, it has examined the nationality of the companies directly providing supply-chain products or services to each of these projects. From this, we are able to draw two conclusions. The first is that around 60–65% of the firms involved were from outside the UK (see Appendix A) and so UK firms were the minority party in delivering these projects. Consequently, floating wind faces a similar challenge to traditional bottom-fixed offshore wind in a bid to grow UK content by 2030.

The second is that the majority of UK activity has been concentrated on providing development and operational services rather than capital expenditure, such as construction, fabrication or supply of core components[31] (e.g. turbine, foundation, moorings, and cables). This supports previous research into the offshore wind sector (BVG Associates, 2015b; Noonan and Smart, 2017; Renewable UK, 2017; Whitmarsh, 2018), suggesting that floating wind is unlikely to be a driving force for significantly growing UK content of capital expenditure across the wind sector. This is in part due to there being no major UK-based floating foundation developers. As identified earlier (see Section 4.2), the UK stands alone as a country with highly ambitious plans for floating wind deployment but without being home to any major floating foundation designers.

It is important to note that these findings are based on the supply chains of just two UK floating wind projects. The extremely small size of our sample means that our findings are highly susceptible to case-by-case conditions. Consequently, if the UK's next floating wind project had a much stronger UK-presence across its supply chain, the picture would change quite significantly. We also note that we cannot simply assume that the coverage of UK firms today across a nascent and very small floating wind sector will be mirrored by a much larger, more mature sector tomorrow. For instance, as the UK accumulates more experience of deploying floating wind projects, we may find that the number and size of companies capable of delivering supply-chain content may grow.

Finally, it is important to note that some non-UK headquartered firms have major operations based in the UK. For example, German firm Siemens, which supplied the turbines for Equinor's Hywind array in the UK, has a blade manufacturing and turbine pre-assembly plant in Hull. Similarly, MHI Vestas,[32] which supplied the turbine for Kincardine phase 1, and expected to do the same for phase 2, has a turbine blade manufacturing facility on the Isle of Wight. These operations create both direct and indirect jobs, whilst growing the UK's skills in this sector.

We acknowledge that to date project developers will have likely sourced suppliers on the basis of both cost and reputation; two factors that do not necessarily align themselves with growing domestic content. If the UK Government and devolved administrations are serious about growing domestic content as a driver of economic growth, then incentives will need to be put in place that will encourage project developers to engage with UK-based suppliers.

Policy recommendation 4

To date, the UK has captured a relatively small share of the floating wind supply chain, especially with regard to capital expenditure. To maximise floating wind's contribution to the UK economy, it is critical that UK firms capture a larger share of the supply chain. To achieve this aim, Government should first **help support UK firms to identify and take advantage of new supply-chain opportunities unique to floating wind. In parallel, it should help to support firms already engaged in the wind supply chain, or other sectors with potential overlapping capabilities (e.g. oil and gas), to transition into it**. Initiatives such as the Offshore Wind Growth Partnership are well placed to help grow UK content of floating wind, as well as of traditional bottom-mounted, foundations.

30 'UK Content is the percentage of the total undiscounted expenditure by the Wind Farm Asset Owner on a Wind Farm that is ultimately spent through Contracts awarded to companies operating in the UK. It excludes the value of Contracts to UK companies that is spent on Subcontracts to companies not operating in the UK. It includes the value of Contracts to non-UK companies that is spent on Subcontracts to companies operating in the UK' (BVG Associates, 2015a p.4). Expenditure includes development, operational and capital expenditure.

31 As outlined in Section 8.2.2 some wind power technology companies have significant operational capacity based within the UK, such as Siemens and MHI Vestas, which translates into jobs.

32 A joint venture between Mitsubishi Heavy Industries (MHI) and Vestas Wind Systems A/S (Vestas) but headquartered in Denmark.

8.2.2 Reliance on EU-based suppliers

The UK's two flagship projects - Hywind and Kincardine – have been highly reliant on supply-chain goods and services from EU- or European Economic Area (EEA)-based companies. For example, 12 out of the 21 companies[33] directly involved in Kincardine were from outside the UK but EU based. For Hywind Buchan Deep, 11 companies were non-UK but EU based. Furthermore, a further 10 companies were from Norway and thus part of the EEA, bringing the total to 21 out of 36 companies that were effectively drawn from within the EU single market.[34]

The UK is expected to leave the European Union on 31 October 2019, at which point the expectation is that it would also leave the EEA (Clifford Chance, 2016; Doherty et al., 2018). This raises two immediate concerns for the floating wind, and by extension the wider offshore wind market: tariffs and supply-chain disruption. As explained by RenewableUK: 'new tariffs, customs procedures or other barriers could disrupt supply chains for manufacturers and risk driving up costs, which would ultimately be borne by consumers' (2019a). These concerns have been echoed by the Wood Group too, with a no-deal Brexit potentially leaving key offshore wind components subject to an average 2.7% WTO import tariff and projects exposed more broadly to uncertainties around component delivery and access to skilled employees (ReCharge, 2019).

This reinforces the argument for the UK to grow the content of its offshore wind sector, not just for the economic growth reasons as outlined in Section 8.2.1 but for two further reasons: (1) to enhance energy security, by ensuring we have access to the products/services necessary to deliver floating wind projects and diversify our portfolio of renewables generation; (2) to minimise the cost of the projects and their electricity supply by avoiding import tariffs.

This arrangement also cuts both ways: UK projects rely on the EU/EEA floating wind supply chain and vice versa. Whitmarsh (2018) points to how companies such as CWind – an operational vessel supplier – and JDR Cables – a sub-sea cables supplier – are actively involved in EU offshore wind projects. The ORE Catpult's analysis finds that, if global floating wind-installed capacity grows to 4 GW by 2030 and strategic investment in infrastructure is made, the UK's maximum export value could reach £230m by 2031 (ORE Catapult, 2018). Both their analysis and ours highlight the number of growth markets in the EU, such as France, Spain and Portugal. Consequently, the imposition of tariffs and wider supply-chain disruption could seriously undermine UK firms' ability to deliver cost-effective products or services to their European market. Any reduction in revenues would in turn impact upon the health of these companies and their ability to deliver floating wind projects at home, in the UK.

Policy recommendation 5

It is expected that future UK floating wind projects will heavily rely on products and services from EU/EEA countries and vice versa. However, questions remain about the affordability and accessibility of trading with Europe post-Brexit. Key issues relate to tariffs and customs procedures for products, as well as the free movement of skilled labour.

The **UK should therefore carefully consider how withdrawing from the EU will impact on the cost and delivery timeline of floating wind projects, as well as the financial performance of UK offshore wind companies from both a domestic and export market perspective. Joint consideration should be given by both the UK and European Governments to the trading arrangements required to support future growth of floating wind in Europe**.

33 For the purposes of this calculation we count MHI Vestas as an EU company, although it is a joint-venture with Japanese based Mitsubishi Heavy Industries.
34 'The EEA Agreement extends the EU single market and free movement of goods, services, people and capital' (Doherty et al., 2018 p.6)

9

Conclusions

9.1 Past and emerging market trends

Floating wind technology is at an important juncture in its lifecycle, on the cusp of progressing from pre-commercial demonstration to large-scale commercial deployment. Since 2008, the sector has enjoyed strong growth, progressing from almost zero installed capacity to 57 MW from 12 projects across six countries by 2018. The UK is currently the world leader in terms of installed offshore floating wind capacity, home to 32 MW and 56% of global capacity, with Japan a close second with 19 MW of deployment.

Looking forward, we find a healthy pipeline of floating wind projects at an advanced stage of planning (i.e. at least applied for consent), with 14 projects planned for commissioning across nine countries, which together would deliver 268 MW of installed capacity by 2022. This is almost five times today's installed capacity. The vast majority of this capacity would be in France and the UK, but with a sizeable share also to be deployed in Portugal, Spain, Japan and the USA. Another 24 projects are at a very early stage of planning, and would deliver a further 5.9 GW of installed capacity, should they all be commissioned potentially before 2030. This is equivalent to around 70% of the UK's current installed capacity of offshore wind. Almost three quarters of this capacity would be deployed by the USA and the UK.

We note two important trends here. The first is that some of the first countries to deploy floating wind have no recent installations or major plans for deployment, such as Denmark and Italy. Second, there are a number of new entrants that are moving into the floating wind market, such as Spain, France and the USA. This is likely to add further competition to the marketplace and help grow the wider supply chain. Second, there is a clear correlation between the countries with a strong floating wind pipeline and those where there is already an attractive investment environment for offshore wind (see EY, 2019).

So how much floating wind capacity could be installed by 2030? Taking the proportion of UK offshore wind projects that have historically moved from pre-consent application to commissioning, we estimate approximately 4.3 GW of floating wind capacity could realistically be commissioned globally by 2030. This growth trajectory is broadly in line with how quickly traditional bottom-fixed floating wind grew at a similar stage in its life-cycle. It is, however, important to note that: (a) some projects may lapse to beyond this date; (b) the pipeline is made up of a handful of very ambitious projects beyond 500 MW that carry a significant risk of never being commissioned; and (c) the estimate is based on project success rates for the UK (not globally) and bottom-fixed offshore wind (not floating wind).

Not all countries that lead in terms of deployment are leaders of floating foundation designs. Most notably, the UK has no major floating foundation suppliers. In contrast, Japan ranks only second to Norway in terms of its installed capacity delivered by domestic firms. Norwegian firms account for over half of the current installed capacity, and this is almost exclusively accounted for by Equinor's 30 MW Buchan Deep array off the coast of Eastern Scotland. Looking to projects that have at least applied for consent, the USA is expected to assume the lead with a 41% market share, largely driven by Principle Power's semi-submersible concept. France would rank second with 21% and Norway third with 12%. The pre-consent application pipeline indicates that the USA will retain its lead to the 2030s, but faces stiff competition from France, which would account for a similar share so that together they would make up almost three quarters of all capacity.

We find that whilst SMEs play a central role in driving growth in the sector (e.g. Principle Power), multi-national energy firms are also playing a key role. These include oil and gas majors (e.g. Equinor), energy utilities (e.g. Iberdrola) and OEMs (e.g. Siemens Gamesa) which have engaged strongly in both floating foundation design and project development. On the one hand, this is a positive sign for future growth, as the sector is able to leverage these companies' financial and political capital. On the other, it creates a pressure on floating wind technology to deliver utility-scale power generation within a relatively short timescale. Public sector investment to support full-scale demonstration will be critical to resisting the pressure to prematurely commercialise floating wind, which could lead to catastrophic technical failures and harm its perceived legitimacy.

9.2 Past and emerging technology trends

Today, there are roughly an equal number of projects employing spar and semi-submersible designs, but spar floaters account for about two thirds of installed capacity, primarily via Equinor's Hywind. Looking forward to the post-consent application pipeline, we find instead that semi-submersible foundations are expected to dominate by 2022, with 65% of global capacity. We also note a larger proportion of future projects employing TLP or other foundation designs compared with today. Looking even further ahead at early-stage planning projects, the market share of capacity is 98% for semi-submersible foundations.

Two key trends emerge. First, in the medium term (i.e. up to 2022), there is a diversification of foundation types, which we expect is a function of projects' individual characteristics aligning with the specific strengths of each floater design category. Second, whilst semi-submersible is expected to dominate the market, many of the foundation designs are variations on the common single foundation, single horizontal-axis turbine design. Variations centre around: (1) situating multiple turbines on single foundations; (2) alternative turbine types (e.g. kite, vertical axis); and (3) co-locating wind with other forms of renewable generation (e.g. wave, solar). These alternative designs could account for a sizeable share of capacity if all planned projects are commissioned and would make for a substantially more heterogeneous marketplace.

Over the past ten years, floating wind projects have exhibited evidence of technological 'scaling up'. For example, turbine power output has more than tripled, whilst turbine hub height has almost doubled. However, less progress has been made in terms of the number of foundations per project. Most projects employ single turbines, the major exception being the Hywind array in the UK. Compared with ten years ago, we are deploying larger-scale turbines, but they are typically still part of single foundation demonstration projects. Looking forward, however, multi-foundation arrays with turbines greater than 5 MW would become commonplace, with three 8 MW turbines already being installed off the coast of Portugal.

A similarly mixed picture is found with projects' geographical characteristics, with distance from shore almost doubling, whilst the average depth of floating wind projects has remained at approximately 60 m. It is unclear whether the focus on these moderate depths are a consequence of technological limitations, attempts to mitigate technical risk or merely developers taking advantage of the shallower sites first. Looking forward to the 2030s, we find a host of extremely large-scale ambitious projects in very deep and remote waters. These are on average over 200 MW, in waters regularly deeper than 250 m and 25 km offshore.

9.3 Future research

This report primarily offers a view on the state of the floating wind sector, both today and tomorrow. A great deal of further research is required, including the following:

a) Robust modelling of the potential growth of the floating wind market under different scenarios;
b) Assessment of the costs of existing floating wind projects, how these costs are disaggregated and which factors have been responsible for changes in costs over time;
c) Comparison of countries' different domestic content of their floating wind projects and the underlying reasons. Also what new supply chain products/services opportunities the floating wind sector presents and what additional capacity is required to support market growth?
d) Assessment of countries' public and private investment into floating wind projects and the extent to which this has served to accelerate deployment.

9.4 Special focus: UK floating wind

Today the UK, and more specifically Scotland, is the world leader in floating wind deployment, with 32 MW split across two projects. It has undoubtedly led the world in terms of the scale and ambition of projects, and this trend is likely to continue. By 2022, this could rise to 78 MW if we consider projects that have at least applied for consent. However, there is also a further 1.9 GW in the pipeline that have yet to apply for consent.

Importantly, however, almost two thirds of the companies directly involved in delivering the UK's two existing projects are from outside the UK. The UK stands alone as a country with highly ambitious plans for floating wind deployment but without any major floating foundation designers. However, this reliance on non-UK firms is not just restricted to foundations but stretches across the supply chain.

Reflecting previous studies (BVG Associates, 2015b; Noonan and Smart, 2017; RenewableUK, 2017; Whitmarsh, 2018), we find that UK firms were mostly involved in project development and O&M, but much less involved in capital expenditure, such as turbines, foundations, etc. It remains unclear what new opportunities floating wind may present the UK to increase its content of the offshore wind supply chain. Nor can we safely assume that the coverage of UK firms today across the two current projects will be representative of much larger sector tomorrow, which may have accumulated significant skills and capacity across the supply chain.

Even so, today the overwhelming majority of non-UK firms involved in delivering the UK's projects are either from the EU or the EEA (e.g. Norway). Brexit therefore raises serious questions about how leaving the single market and the customs union may impact negatively on the prospects of future UK floating wind projects, due to tariffs, supply-chain disruption and lack of access to skilled labour. It also raises concerns about the health of the UK firms involved in floating wind, which currently export products or services to EU countries. A weakening of these firms may erode the UK's capacity to deliver its current pipeline of floating wind projects. In parallel, Brexit may mean that the UK is unable to access a wealth of demonstration grant funding made available by the EU (e.g. Horizon 2020, EU Innovation Fund, etc).

Finally, we note how both UK floating wind projects that have been delivered to date have relied heavily on the Renewables Obligation, which has now been discontinued. No analogous scheme has been put in its place to support pre-commercial power generation. Instead, floating wind developers are left with the CfD as the only route to subsidy, but are expected to struggle to be eligible for the scheme and to compete in it with much cheaper forms of power (e.g. from bottom-fixed offshore wind).

Should the UK fail to replace the RO with a similar mechanism and/or retain access to EU innovation funds, UK floating wind projects are unlikely to be able to source the patient pre-commercial capital they require to drive costs down. In the absence of such subsidy, servicing niche markets that have above-average electricity costs (e.g. wind-to-gas, islands) is likely to offer an important path for future floating wind projects and to drive down costs through economies of scale.

In this context, we present a summary of our five recommendations for the UK and devolved governments:

1 EU innovation support

Move to retain access to EU demonstration funding post-Brexit. If unsuccessful, the UK must consider how it can use its own public funds to cover any shortfall, with a focus both on demonstration grants and government-backed finance.

2 Long-term pre-commercial subsidy

With the RO now discontinued, there is no longer an appropriate, long-term subsidy to support pre-commercial floating wind projects. One option would be to create an innovation-oriented CfD pot that allows for more expensive pre-commercial technologies (e.g. floating wind, tidal stream) to compete against one another for a guaranteed strike-price.

3 Niche markets

The Government could usefully fund a study to identify potential niche markets in the UK for floating wind (e.g. oil and gas extraction, island consumption), the associated cost benefits and barriers to deployment. Findings would inform what additional support is required for developers to access these markets.

4 Grow UK supply chain content

Help support UK firms to identify and take advantage of new supply-chain opportunities unique to floating wind. In parallel, help firms already part of the traditional offshore wind supply chain, and those from other sectors with overlapping capabilities, to transition into the floating wind sector.

5 Minimise supply chain disruption

Consider how withdrawing from the EU will impact on the cost and delivery timeline of floating wind projects in both the UK and Europe, as well as the financial performance of UK offshore wind companies from both a domestic and an export market perspective. In turn, consideration should be given to what trading arrangements (e.g. tariffs) will support the future growth of floating wind in the UK and Europe more widely.

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Appendix A
Hywind and Kincardine supply chains

Supply chain components	Hywind Buchan Deep		Kincardine	
	Company	Country	Company	Country
Project ownership, management and planning				
Project management and ownership	Equinor (75%)	Norway	ACS Group (owns Cobra)	Spain
	Masdar (25%)	UAE	-	-
Surveys				
Metocean	Metocean Services International	South Africa/Australia	-	-
Geotechnical	Fugro GeoConsulting Limited	UK	Fugro GeoConsulting Limited	UK
Environmental Impact Assessment	Xodus Group	UK	Atkins	UK
Consultancy	-	-	-	-
Technical due diligence	Wood Group	UK	SENER Group	Spain
Fabrication support (e.g. substructures)	Aibel	Norway	-	-
Sub-component and system engineering	Aibel	Norway	-	-
Procurement	Aibel	Norway	-	-
Manufacturing	-	-	SENER Group	Spain
Marine warranty services	Global Maritime	Norway	-	-
Financial	-	-	Green Giraffe	Netherlands
Turbine supply				
Turbine	Siemens*	Germany	MHI Vestas	Denmark/Japan
Casting and forgings	Pioma-Odlewnia Sp	Poland	-	-
Tower	Navacel	Spain	-	-
Port services for turbine assembly	Norsea AS (Stordbase)	Norway	-	-
Balance of plant supply				
Floating foundation design	Equinor	Norway	Principle Power	USA
Floating foundation fabrication	Navantia	Spain	Navantia	Spain
	Windar	Spain	Windar	Spain
Foundation flanges	Euskal Forging SA	Spain	-	-
Anchors	Global Energy Group (formerly Iselburn)	UK	Vryhof	Netherlands
	NGI (design)	Norway	-	-
Mooring substructures	MacGregor Cargotec	Finland	Vryhof	Netherlands
	-	-	FMGC Farina Group (design)	France
Mooring chains and connectors	Vicinay Marine SL	Spain	Vicinay Marine SL	Spain
	-	-	FirstSubSea	UK
Subsea array and export cables	Nexans Norway AS	Norway	Prysmian Group SPA	Italy
Subsea cable protection	-	-	Trelleborg	Sweden
Cable buoyancy modules	Bardot Group	France	-	-
Onshore battery storage	Aggreko (formerly Younicos)	UK	-	-
Uninterruptible power supply	Eltek Deutschland GmbH	Germany	-	-

Supply chain components	Hywind Buchan Deep		Kincardine	
	Company	Country	Company	Country
Installation and commissioning				
Heavy load logistics	OHT Management AS	Norway	Bourbon Offshore	France
	Technip Norge AS	Norway	Kinetic Renewables Services	UK
Marine coordination	-	-	Asco	UK
Foundation installation	OHT Management AS	Norway	-	-
Lift and mating operations of turbines	Saipem SpA	Italy	Bourbon Offshore	France
Mooring and anchor installation	TechnipFMC	UK	Vryhof	Netherlands
	-	-	Bourbon Offshore	France
Drilling	LMR Drilling	UK	-	-
External installation platform	Navacel	Spain	-	-
Installation cranes	Granada Material Handling Ltd	UK	-	-
Subsea array and export cable installation	Subsea 7	UK	Correll Services (part of RTS Group)	UK
	-	-	Global Offshore	UK
Substation and onshore cabling	Balfour Beatty	UK	-	-
Operation, maintenance and service				
O&M	-	-	Kinetic Renewables Services	UK
Inspection, maintain and repair	Reach Subsea	Norway	-	-
Buoy maintenance	Green Marine	UK	-	-
Monitoring equipment				
LIDAR	Wood Group	UK	-	-
Mooring load monitoring	Strainstall/James Fisher & Sons	UK	-	-
Turbine condition	Kongsberg Renewables Technology	Norway	-	-
Metocean monitoring and weather forecasting	Partrac	UK	Partrac	UK

Source: 4COffshore and supply chain company websites'.

NOTE: Categories adopted from BVG Associates (2014). Correct as of 1st June 2019.

* Siemens Green Port Hull is responsible for blade manufacturing and turbine pre-assembly.

Notes