Floating Offshore Wind: A Situational Analysis

Dr. Roberts Proskovics

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Introduction

Floating offshore wind technology is gaining momentum, with more governments and organisations showing interest in its potential to unlock wind resource from deep water sites. As a relatively nascent technology, floating wind has several barriers to overcome before it can be deemed a fully-commercial technology. This Analysis Paper looks at the key strengths, weaknesses, opportunities and threats (SWOT) surrounding floating offshore wind and its path to full commercialisation, and is aimed at those who might have technical knowledge of bottom-fixed offshore wind, but little or no previous exposure to floating wind technology.

Headlines

- A clear frontrunner as to the most viable substructure type (semi-submersible, spar and tension-leg platform (TLP)) and primary material (steel or concrete) is yet to emerge.
- Currently, TLPs lag behind the other typologies in terms of technology readiness.
- Floating offshore wind turbine substructure design should not be optimised against one parameter only, as this can lead to an overall increase in the cost of the substructure (e.g. a substructure optimised solely for mass could become more complex to manufacture).
- While floating offshore wind is exposed to various technological challenges (e.g. technology readiness level progression, development of dynamic export cables), the most significant challenges are commercial.
- Floating offshore wind remains a relatively nascent technology and is predominantly deployed in demonstration projects. The next step in its commercialisation will be the development of pre-commercial projects. These require government support, which is available in only a few countries.
- The commercialisation of offshore wind can unlock additional benefits such as employment in economically and socially deprived areas, and inject life into ports.

SWOT Analysis

Figure 1: The HyWind Scotland project's last floating offshore wind turbine sets sail from Stord, Norway, en route to its destination off Peterhead, Scotland. Credit: Øyvind Gravås/Equinor

The following boundaries were used for this strengths, weaknesses, opportunities and threats (SWOT) analysis:

- The analysis is design-agnostic (i.e. it compares substructure types and not specific designs)
- Barge technology is grouped with semi-submersible
- Hybrid technologies, multi-energy conversion systems and multi-turbine designs are not considered
- While some comparison between bottom-fixed and floating offshore wind is made, this is not a key objective of this paper.

Strengths and Weaknesses of Floating Offshore Wind

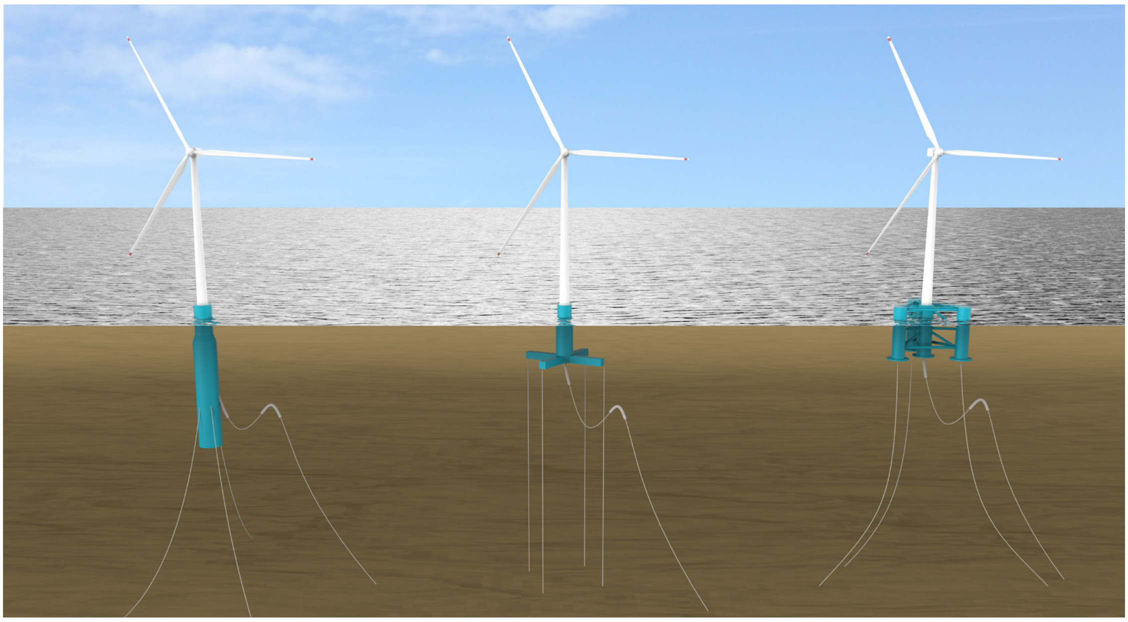

Figure 2: Floating wind typologies (left to right: spar, tension leg platform (TLP), semi-submersible)

The strengths and weaknesses of floating offshore wind are assessed under five key headings on a typology basis (see Figure 2, above). In other words, semi-submersible, spar and TLP-type substructures are compared against each other with the main strengths and weaknesses of each highlighted. While no direct comparison between bottom-fixed and floating offshore wind is provided (see [1] for a risk and cost comparison between both technologies), some of the main differences can be inferred (e.g. discussion on the ability to use ports for maintenance work, which is not applicable to bottom-fixed offshore wind).

Stability and Sensitivity to Waves

Semi-submersibles and spars have an inherent stability that is not present in TLPs. This inherent instability is design-specific – early TLPs, such as TLPWIND, PelaStar and the first iterations of the GICON system, were inherently unstable and required bespoke installation vessels. The more recent TLPs (e.g. SBM Offshore, X1Wind and the latest GICON design) claim to be self-stable. While self-stability is beneficial, as it allows for the use of cheaper, less complex vessels for installation, the margin of stability will be lower for self-stable TLP designs, compared to those using a bespoke vessel when in tow or being installed on-site. This can have an adverse effect on installation windows, making bespoke vessels a worthwhile investment for large wind farms: these can also be reused in the operations and maintenance (O&M) and decommissioning phases, and could increase the transit speed.

A floating wind substructure's sensitivity to waves is a function of different parameters. The shape and dimensions of the substructure at and near the water line is a key parameter. Spar and TLP designs have a small cross-sectional area at the water level, making them less sensitive to waves. Spars are inherently of a long and slender design, which can be further improved by tapering the design to a smaller diameter at the water line, as it is done in Hywind. TLPs rely on having a large buoyancy force to weight ratio, which results in the majority of the substructure being well below the water line, reducing variation in the buoyancy forces as wave crests and troughs pass. On the other hand, semi-submersibles gain some of their stability by having a large waterplane area, which makes them more sensitive to wave forces.

Technology

In terms of Technology Readiness Level (TRL), only spar and semi-submersible (including barge) designs have been proven using a full-scale prototype. The Dutch developer Blue H Engineering demonstrated a scaled 80kW prototype (not connected to the grid) in 2008 for a six-month period.

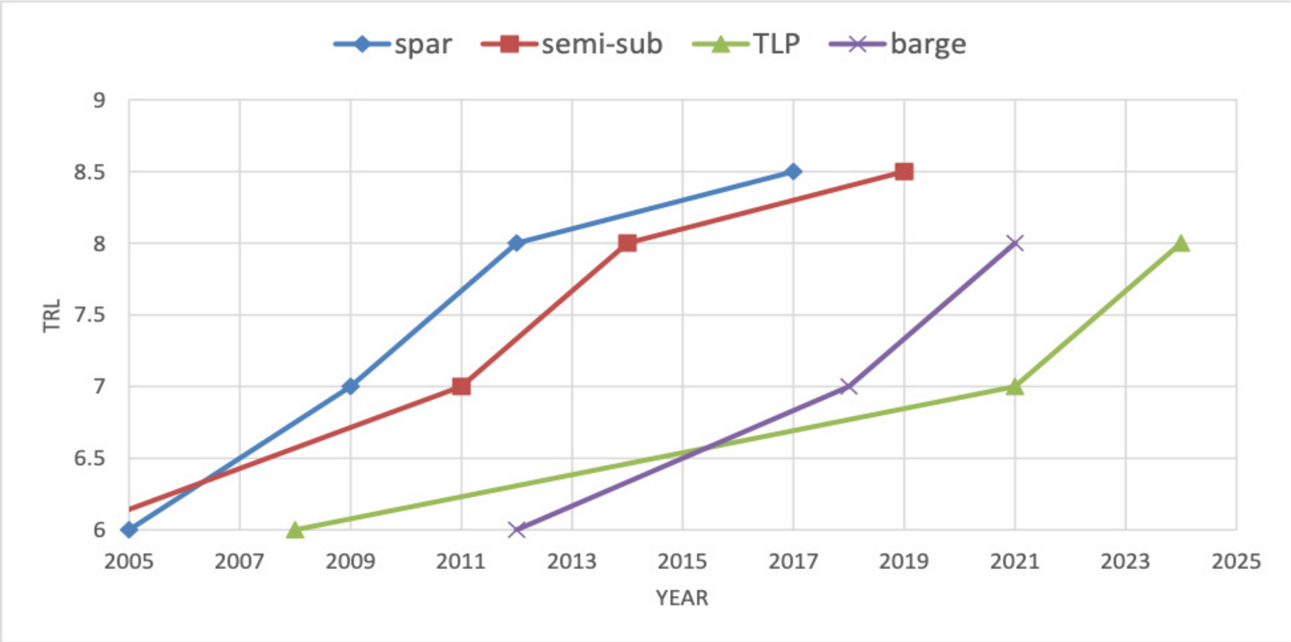

Figure 3: TRL progression for each substructure type.

Figure 3 shows TRL progression for each typology using the European Commission's TRL definition [2], interpreted as:

- TRL 6: Wave basin testing or a small-scale prototype
- TRL 7: Full-scale prototype
- TRL 8: Full-scale prototype operational for three years
- TRL 9: Technology in its final form.

The spar, semi-submersible and barge lines in Figure 3 represent the development stages of Hywind, WindFloat and Ideol, respectively. The TLP line is a combination of Blue H's design (TRL 6) and the Provence Grand Large project that will utilise a design by another Dutch developer, SBM Offshore. Technology readiness level 8.5 represents a step in the optimisation of the technology using the learning from a prototype (e.g. the dimensions of the spars used in the Hywind Scotland are very different to those of the original Hywind design [3]).

Wind turbine control complexity is directly related to the dynamic response of the design. Semi-submersibles are relatively sensitive to wave forcing, making their turbine control more complex. Spar designs are prone to "nodding" motions, which can lead to negative aerodynamic damping. However, TLP control is much simpler and, except for a few modifications, is very similar to that of a bottom-fixed offshore wind turbine.

Wind turbine controller systems will have to be modified for all designs of floating wind turbines. However, this is not an insurmountable challenge – as shown by Equinor, which developed a bespoke controller for its Hywind design that has led to very favourable dynamic response motions.

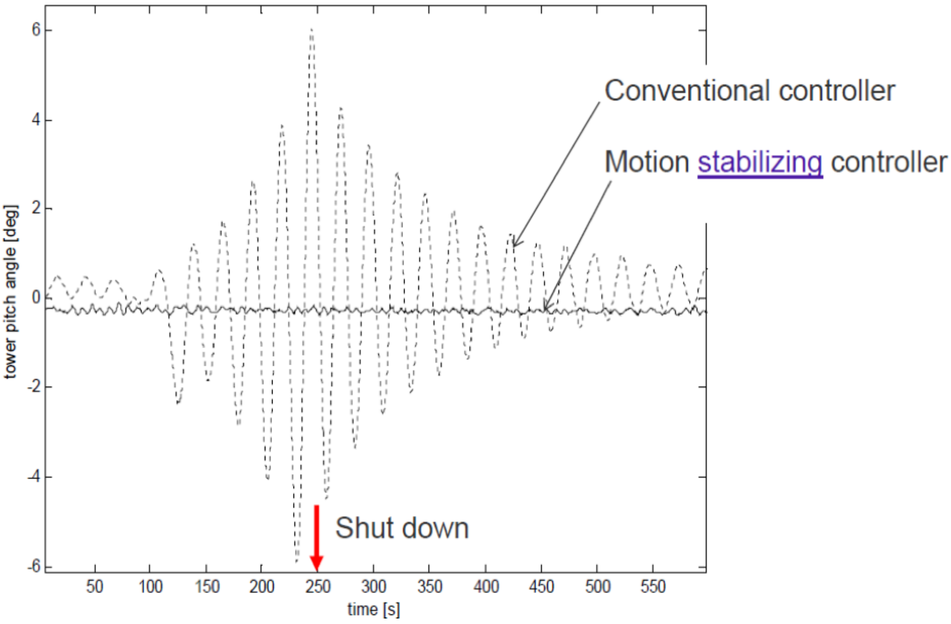

Figure 4: Hywind tower response with conventional and bespoke wind turbine controller.

Shown above in Figure 4 is a numerically-simulated Hywind tower fore-aft response with a conventional and a bespoke controller developed by Equinor. The conventional controller leads to much higher amplitudes of tower motions, resulting in an eventual wind turbine shutdown at 250s. Even after the shutdown, the systems continue to oscillate. On the other hand, the bespoke controller offers a much smoother system response, which leads to increased power generation and reduced loading on the system.

Lifecycle Phases and Water Depth Restrictions

Installation requirements are linked to the stability of substructures. Semi-submersibles are self-stable and hence can be installed using relatively low-cost tugs and anchor-handling vessels, which makes semi-submersibles the least expensive in terms of installation costs. However, stability is not the only parameter that influences installation procedures: substructure dimensions are as important. Spars are self-stable, but because of their large draft, these require heavy-lift vessels or bespoke installation solutions for attaching the turbine to the substructure. In terms of dimensions, TLPs are more comparable to semi-submersibles, but because these are typically not self-stable these require bespoke installation vessels (see Stability for a discussion on self-stable TLPs).

Assembly, maintenance and decommissioning can be performed in port for semi-submersible and TLP designs. Spars, because of their large draft, cannot be fully assembled, repaired and decommissioned at port. For spars these tasks can be performed either in sheltered waters that can improve weather windows or on-site. For the same reasons, spars are not suitable for water depths below 80m, whilst semi-submersibles and TLPs are (from approximately 30m and 60m, respectively. This is also dependent on design and turbine rating).

Structural Features and Manufacturability

TLP designs have considerably lower mass than semi-submersibles and spars. This is a consequence of TLPs having a large buoyancy-to-weight ratio. Spar substructures are the simplest in terms of shape. These are highly uniform structures with no multi-plane joints, which makes them easier and cheaper to manufacture.

Mooring System

The mooring system can be tailored for each design. Typically, semi-submersible and spar type designs tend to utilise simple catenary chain mooring lines and drag-embedded anchors, while TLPs are limited to tendons (the material used for tendons can differ from metal wire to synthetic ropes) and piles that need to provide much higher vertical holding forces. This makes the TLP's mooring systems more complex and more sensitive to the seabed conditions, making it more expensive, both in terms of hardware and installation costs.

Compared to spars and semi-submersibles, TLPs have a reduced ability to cope with extreme weather events such as tsunamis, earthquakes and seabed movements. Tension leg platforms rely on their mooring system for stability, which can be compromised by soil liquefaction as the result of an earthquake, or large changes in the buoyancy-to-weight ratio due to a tsunami. At the same time, TLP designs have a much smaller footprint as their mooring system is vertical to the substructure. It is not unusual for catenary systems to have a footprint radius of eight to ten times the water depth. High tensions in the tendons mean that TLP motions are reduced to a smaller number of degrees-of-freedom (mainly surge and sway), as shown in Figure 5.

Figure 5: Degrees of freedom of a floating offshore wind turbine

Steel and Concrete Designs

The majority of floating offshore wind substructures have been made from steel (e.g. Hywind, WindFloat, Fukushima Mirai and Shimpuu). This is reflective of the bottom-fixed offshore wind and offshore oil and gas industries, which are dominated by steel structures. However, lately there has been an increase in the number of proposed floating wind designs that use concrete as the primary material (for example, Ideol, OO-Star, ACS Cobra and VoltornUS).

Concrete is a robust material that can provide a long service life. However, the benefits of the concrete's longevity in offshore wind are yet to be proven. For example, a wind turbine model installed on a 50-year design life substructure might not be available on the market by the time its design life of approximately 25 years has elapsed. Concrete is also cheaper per unit of mass and is not exposed to high price volatility like steel, but it does increase the mass and size of substructure compared to steel designs. In terms of fabrication, concrete can be used in any country, unlocking local content benefits which can be crucial to securing support from the government (especially for early projects that will depend on government subsidies). At the same time, due to the typically larger sizes and mass compared to steel designs, concrete designs could require larger investments in port facilities to make them viable for mass production of floating wind substructures.

Steel substructures have a long history of being used offshore and steel is much easier to recycle. However, it is subject to corrosion (so is concrete via internal reinforcements, but to a lesser extent). Floating wind substructures made of steel can be assembled faster as these are not as sensitive to environmental conditions (e.g. frost and heavy rain) and are not exposed to curing time, as concrete designs are.

Both steel and concrete have their advantages and disadvantages, and a clear "winner," if one exists, is yet to emerge.

Steel	Concrete
Pros	Pros
Long history of being used offshore	High local content
Easier to recycle	Low cost of raw material per tonne
	Long service life
Cons	Cons
Subject to corrosion	Increases mass and size of substructure
High cost of raw material per tonne	Requires larger investment in port facilities
Steel price volatility	Environmental sensitivities (e.g. frost, heavy rain)
	Curing time

Table 1: Pros and cons of using steel and concrete for floating offshore wind substructures.

Opportunities and Threats for Floating Offshore Wind

Like any other technology, floating wind has many opportunities and threats. Broadly speaking, these can be grouped into the following categories:

- Environment and potential sites
- Technology
- Financial support and route to market
- Supply chain.

While the strengths and weaknesses were analysed from the perspective of typology and material, opportunities and threats are viewed from an industry-wide perspective (i.e. what are the main selling points and challenges that could make or break the industry?).

Environment and Potential Sites

This section covers those aspects of floating wind that are directly linked to the environmental conditions at installation sites. This includes, but is not limited to, the impact of floating wind on the local marine life and fauna, stakeholders, bathymetry, and wind and wave conditions.

Opportunities

- Suitability for deep water sites, hence opening new markets*
- Access to sites with strong and consistent wind speeds (e.g. Hywind Scotland achieved 65% capacity factors over the 2017/18 winter period [4])*
- Reduced marine impact (e.g. reduced piling, reduced soil disturbance in installation and decommissioning, less cable burial)
- Potential to construct floating offshore wind in developed but later abandoned bottom-fixed offshore wind sites (e.g. complex seabed conditions)
- Ability to cope with extreme weather events (e.g. tsunamis, earthquakes, seabed shifting).

Threats

- Environmental or other stakeholder opposition to floating offshore wind deployment (e.g. fishing, defence, shipping).

** Also applicable under "financial support and route to market"*

Technology

Technology covers aspects that are related to the machinery and equipment required for floating offshore wind to operate. These include, but are not limited to, technology readiness, electrical equipment and wind turbine control.

Opportunities

- Maturation of floating wind (i.e. progression of typologies along the TRL scale and cost parity with bottom-fixed offshore wind)
- Highly standardised substructure (very little or no adaptations within and between wind farms)
- Positive scaling of substructures (e.g. a substructure for a 10MW turbine will have only two times the mass of the substructure for a 2MW turbine [5]).

Threats

- Potential warranty issues with respect to turbine control modifications (all floating offshore wind turbines will require some control modifications)
- Substations for deep waters (little experience)
- No dynamic export cables are yet available on the market.

The last two threats were also highlighted as the key innovation needs by the Floating Wind Joint Industry Project [6].

Financial Support and Route to Market

Financial support and route to market deals with questions related to raising finances for floating wind, possible routes to market, risks, and any economic aspects that could prohibit floating wind from becoming a mainstream technology. These include, but are not limited to:

Opportunities

- Direct electrification of offshore oil and gas platforms as investigated by the WIN-WIN project [7] and proposed by Equinor for the Hywind Tampen project
- Power generation for island communities with limited space for onshore generation and no direct link to mainland (e.g. the Canary Islands, Hawaii)
- Push for renewable energy (e.g. Paris Agreement)
- Energy security
- Increased options to locate farms close to load centres
- Similarities with oil and gas platforms resulting in investment interest from major players in oil and gas (e.g. Aker Solutions' investment in WindFloat and Siem Offshore Contractors investing in Ideol)

- Total floating wind cumulative market of up to 100GW by 2050.

Threats

- Large number of designs, which points towards an immature technology
- Lack of government support (floating wind is still dependent on subsidies)
- A single floating foundation supplier becoming dominant in the market
- Perception (e.g. seen as risky investment by investors)
- Lack of clear route to market in many countries
- High cost of capital for early projects in comparison with current bottom-fixed wind.

Supply Chain

This section deals with the supply chain for production of floating offshore wind projects. This includes, but is not limited to, material requirements and pricing, jobs, similarities and competition with other similar industries.

Opportunities

- Reuse of the supply chain developed by bottom-fixed offshore wind, oil and gas, and shipbuilding
- Lessons learned from bottom-fixed offshore wind, oil and gas, and shipbuilding
- Job creation
- Local content (particularly for concrete designs and steel producing nations)
- Most designs only require standard vessels for installation, O&M and decommissioning
- Reduced risk profile related to offshore installation, as most operations are completed onshore.

Threats

- Steel price volatility
- Continued downwards pressure on costs from bottom-fixed wind, making early commercial-scale floating wind projects seem expensive
- Recovery of the oil and gas industry leading to increased competition for the supply chain
- Requirement for investment in port facilities
- Lack of consolidation in design preventing supply chain optimisation and further cost reduction
- Turbine manufacturers are currently unwilling to implement major wind turbine design changes for floating offshore wind.

In addition to the points raised above, some aspects of floating wind are location-dependent. For example, conflict of space usage with fishing vessels, coastal navigation and recreational sailing will be higher near shore. However, because floating wind turbines can also be installed in deeper waters far offshore, conflict is reduced.

Visual impact is another aspect that is highly location-dependent. In some cases, there may be opposition to any offshore wind turbines installed close to shore. This is reduced if turbines are installed further offshore. Visual impact from floating wind turbine manufacturing, assembly, repair (near shore or in port) and decommissioning is expected to encounter less opposition as these are short-period tasks that will bring jobs to the area.

Additional Benefits of Floating Offshore Wind

Floating wind will bring investment and support direct and indirect jobs (fixed-term jobs in the project development, construction and decommissioning stages and permanent or long-term jobs in the operations stage), often in economically and socially deprived areas.

Similarities between the oil and gas and floating wind industries could allow floating offshore wind to absorb and maintain facilities, skills and know-how during downturns in the oil and gas industry.

The investments in ports that will be required for commercial-scale floating offshore wind have the potential to introduce new industries to ports – or bring back those that have left (e.g. those that would not be able to pay for the infrastructure development or require ports to be heavily utilised to be operational, for example, refineries).

Conclusion

There are three main floating wind substructure types, each with its own strengths and weaknesses. For a relatively nascent technology, a large number of designs have already been proposed. However, new designs are still emerging, some of which look to combine the advantages of other substructure types.

For a specific project, the most appropriate design will be dependent on the site conditions and supply chain availability. Concrete designs could be preferred in countries with no domestic steel industry or in projects that require high local content, such as pre-commercial projects that rely on government support.

The upcoming pre-commercial, multi-turbine projects – such as Equinor's 88MW Hywind in Norway and Ideol's 24MW Eolmed project in France – will further strengthen the case for floating wind as a technology for clean electricity generation. These projects will also encounter and overcome various challenges. However, it will be large, fully-commercial projects, like Principle Power's 120MW development off the coast of California, that will pave the way for floating wind becoming a mainstream technology by benefitting from the effects of scale, lowering the cost of energy, and solving capital-intensive, floating wind-specific challenges.

Appendices

Table: Strengths and Weaknesses

Provided below is a table highlighting the key strengths and weaknesses for the three typologies reviewed. Strengths and weakness are linked to different characteristics of each typology. Whether a particular characteristic is a strength or a weakness for a specific typology can be identified by the whether the characteristic is or isn't applicable to the typology. For example, semi-submersibles and spars are self-stable, which is a strength, whilst TLPs are not self-stable, which is a weakness.

		Semi-Submersible		Spar		TLP	
No.	Characteristic	Strength	Weakness	Strength	Weakness	Strength	Weakness
1	Self-stable	Yes		Yes			No
2	Sensitive to waves		Yes	No		No	
3	Proven technology	Yes		Yes			No
4	Simple wind turbine control		No		No	Yes	
5	Installed using widely-available and low-cost vessels	Yes			No		No
6	Port-friendly	Yes			No	Yes	
7	Suitable for water depths <80m	Yes			No	Yes	
8	Low mass		No		No	Yes	
9	Simple, clean substructure		No	Yes			No
10	Small draft	Yes			No	Yes	
11	Small mooring footprint		No		No	Yes	
12	Sensitive to seabed conditions	No		No			Yes
13	Simple mooring system	Yes		Yes			No
14	Reduced degrees of freedom		No		No	Yes	
15	Ability to cope with extreme weather events	Yes		Yes			No

Table 2: Strengths and weaknesses of floating offshore wind typologies.

Table: Opportunities, Threats, and Added Benefits

Opportunities	Threats	
Suitability for deep water sites opening new markets	Environmental or other stakeholder opposition to floating offshore wind deployment (e.g. fishermen, defence, shipping)	Environmental and Potential Sites
Access to sites with stronger and more consistent wind speeds		
Reduced marine impact		
Potential to construct floating offshore wind in developed but-later-abandoned bottom-fixed offshore wind sites		
Ability to cope with extreme weather events (e.g. tsunamis, earthquakes, seabed shifting)		
Maturation of floating wind	Warranty issues with respect to wind turbine control modifications	Technology
Highly-standardised substructures	Substations for deep waters	
Positive scaling of substructures	No dynamic export cables yet available on the market	
Direct electrification of offshore oil and gas platforms	Large number of designs, which points towards an immature technology	Financial Support and Route to Market
Power generation for island communities with limited space for onshore generation and no direct link to mainland	Lack of government support	
Push for renewable energy	A single floating foundation supplier becomes dominant in the market	
Energy security	Perception (i.e. seen as risky investment by investors)	
Increased options to locate farms closer to load centres	Lack of clear route to market in many countries	
Similarities with oil and gas platforms resulting in investment interest from major players in oil and gas	High cost of capital for early projects in comparison with current bottom-fixed wind	
Total floating wind cumulative market of up to 100GW by 2050		

Opportunities	Threats	
Reuse of supply chain developed by bottom-fixed offshore wind, oil and gas and shipbuilding	Steel price volatility	Supply Chain
Lessons learned from bottom-fixed offshore wind, oil and gas, and ship building	Continued downwards pressure on costs from bottom-fixed wind, making early commercial-scale floating wind projects seem expensive	
Job creation	Recovery of the oil and gas industry leading to increased competition for the supply chain	
Local content (particularly for concrete designs and steel producing nations)	Requirement for investment in port facilities	
Most designs only require standard vessels for installation, O&M and decommissioning	Lack of consolidation in design preventing supply chain optimisation and further cost reduction	
Reduced risk profile related to offshore installation, as most operations are completed onshore	Turbine manufacturers are currently unwilling to optimise their designs for floating offshore wind	
Investment and jobs in economically and socially deprived areas		Added Benefits
Support oil and gas industry when price of an oil barrel is low		
Port infrastructure improvements that can help to support other industries		

Table 3: Opportunities, threats, and added benefits of floating offshore wind.

Recommended Reading

A cost and risk comparison of floating and bottom-fixed offshore wind – R. Proskovics and G. Smart, A Buoyant Future – Reducing Cost and Risk in Floating Offshore Wind, Windtech International, volume 13, no. 4, June 2018.

Macroeconomic Benefits of Floating Offshore Wind in the UK – ORE Catapult & Crown Estate Scotland, October 2018.

A detailed cost modelling analysis of a tension-leg platform – A. Spyroudi, Cost Modelling Analysis of Floating Wind Technologies: Assessing the Potential of TLPWIND©, ORE Catapult, 2016.

A comprehensive floating wind market and technology overview – R. James and M. Costa Ros – Floating Offshore Wind: Market and Technology Review, The Carbon Trust, 2015.

A good review of floating wind specific findings and challenges for electrical and mooring system, and infrastructure and logistics – Floating Wind Joint Industry Project, Phase I Summary Report – Key Findings from Electrical Systems, Mooring Systems, and Infrastructure and Logistics studies, The Carbon Trust, 2018.

A comprehensive review of innovations that could lower the cost of floating offshore wind – BVG Associates, Floating Offshore – 55 technology innovations that will have greater impact on reducing the cost of electricity from European floating offshore wind farms, InnoEnergy, 2017.

References

[1] R. Proskovics and G. Smart, “A Buoyant Future: Reducing Cost and Risk in Floating Offshore Wind,” Windtech International, vol. 13, no. 4, 2017.

[2] European Commission, “Horizon 2020,” [Online]. Available here. [Accessed 28 June 2018].

[3] Equinor, “Hywind - leading floating offshore wind solution,” [Online]. Available here. [Accessed 28 June 2018].

[4] Offshore Wind, “World’s First Floating Wind Farm Outdelivers,” Offshore Wind, 15 February 2018. [Online]. Available here. [Accessed 12 September 2018].

[5] Principle Power, WindFloat Atlantic: A step change in turning floating wind commercial, Turku, 2016.

[6] Carbon Trust, “Floating Wind Joint Industry Project Phase I Summary Report - Key Findings from Electrical Systems, Mooring Systems, and Infrastructure & Logistics studies,” Carbon Trust, Lon-don, 2018.

[7] DNV GL, “WIN WIN - WINd-powered Water INjection,” [Online]. Available here. [Accessed 12 September 2018].

Author Profile

Dr. Roberts Proskovics is an engineer at ORE Catapult, and is responsible for ORE Catapult's floating wind project portfolio. His primary work includes risk assessment of floating wind turbines. Prior to working at ORE Catapult, he was involved in dynamic simulations and aerodynamics of spar-type floating wind turbine investigations as part of his PhD.

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Offshore Renewable Energy Catapult

Inovo

121 George Street
Glasgow
G1 1RD, UK
T: +44 (0)333 004 1400

National Renewable Energy Centre

Albert Street, Blyth
Northumberland
NE24 1LZ, UK
T: +44 (0)1670 359 555

Fife Renewables Innovation Centre

Ajax Way
Leven
KY8 3RS
T: +44 (0)1670 357 649

O&M Centre of Excellence

Ergo Centre
Bridgehead Business Park
Meadow Road, Hessle
HU13 0GD