CATAPULT
Offshore Renewable Energy

Floating wind: technology assessment

Interim findings

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1 Executive summary

The Offshore Renewable Energy (ORE) Catapult, as the UK's flagship technology innovation and research centre for offshore renewables, delivers programmes and initiatives aimed at realising the potential for affordable renewable energy generation from the marine environment. As well as working on cost reduction for today's offshore wind sector, ORE Catapult helps develop the innovations for the next generation of offshore renewables. With this in mind, ORE Catapult has started to work with the emerging floating wind sector and is already active in many of the largest research projects at a UK and European level.

This summary paper presents a technology update from the findings of research commissioned jointly by ORE Catapult and The Crown Estate. The work has studied the position of the floating wind sector in relation to technical development**,** deployment volume and cost competitiveness, these factors being considered sound indicators of progress towards both the technological and commercial maturity of the sector.

As floating wind moves along the **Technology Readiness Level (TRL)** index from early research (TRL 1) to system demonstration over the full range of expected conditions (TRL 9) it also begins a commercial journey which can be assessed under the criteria of the **Commercial Readiness Index (CRI).** We observe that Technologies in countries such as the USA and Japan are beginning to make progress along the TRL scale and the CRI path, but technologies and projects in Europe remain the lead with current and near term planned deployment. Overall as a sector we conclude that current status level of floating wind globally is CRI 2 “Commercial Trial”, and has the ability to move up to CRI 3 “Commercial Scale Up” should more than one of the proposed demonstration arrays go ahead and prove successful.

Through consultation with industry we have identified the key technical challenges that are common across the floating with sector, these are; wind turbines, support structures, moorings and anchors, electrical infrastructure, installation and maintenance, and design standards and tools. Many of these challenges identified can be addressed through technical advancements aligned to targeted investments and initiatives, both in terms of engineering design and philosophies. It is clear that significant investment is needed to tackle many of these challenges, and they also present an opportunity for shared costs and risks though collaborative working in the sector.

The final version of this report will be available later this year with key findings presented to the industry in a series of workshops which will establish a mechanism for aligning the requirements of offshore wind farm developers, foundation manufacturers, turbine manufacturers and the supply chain.

2 Introduction

The Offshore Renewable Energy (ORE) Catapult, as the UK's flagship technology innovation and research centre for offshore renewables, delivers programmes and initiatives aimed at realising the potential for affordable renewable energy generation from the offshore marine environment. While focussing on cost reduction for today's offshore wind sector, ORE Catapult has started to shape and support the emerging floating wind sector with the largest established Joint Industry Projects (JIPs) operating at both a UK and European level.

With the potential for floating wind to become a truly global market, capable of capturing and commercially exploiting previously inaccessible regions, future innovation programmes need to be focussed on technological uncertainties, with a targeted approach to cost reduction and commercialisation. ORE Catapult, in partnership with The Crown Estate are working to identify uncertainties in the sector and to identify the role for the UK in the floating wind sector.

This summary paper presents a technology update from the findings of research commissioned by ORE Catapult and The Crown Estate to build on previous research published in 2012.[1] The work has studied the interaction of **Technical Development**, **Deployment Volume** and **Cost Competitiveness**, with these considered as indicators of progress towards both the technological and commercial maturity of floating wind. Developed from research and analysis alongside engagement with key industry stakeholders, it is intended to make the completed report available later in the year.

3 Commercialisation of floating wind

There are certain development phases that are considered to be natural steps in the development process of a new technology. After successful proof of concept in laboratory, concept development and scale testing are often undertaken. The **Technology Readiness Level (TRL)** index is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology from early stage research (TRL 1) to system demonstration over the full range of expected conditions (TRL 9). As a technology moves from TRL 1 to 9 investments must be used intelligently to push forward with technical development, deployment volume and cost competiveness.

[1] The Crown Estate – UK Market Potential and Technology Assessment for floating offshore wind power. An assessment of the commercialization potential of the floating offshore wind industry (2012). Online at http://www.thecrownestate.co.uk/media/5537/km-in-gt-tech-122012-uk-market-potential-and-technology-assessment-for-floating-wind-power.pdf (accessed 15/6/2015)

Whilst the majority of technology risk can be removed as a technology moves through TRL 1 to 9, significant commercial uncertainty and risk remain in the demonstration and deployment phase. A new technology entering a market place that is supplied by proven incumbents and financed by capital markets faces a multi-faceted range of barriers as it is commercialised. The Australian Renewable Energy Agency has developed the **Commercial Readiness Index (CRI)**[2] as a tool that can be used to measure the commercial readiness of emerging renewable energy solutions. The relationship between the TRL and CRI frameworks is illustrated in Figure 1 above.

Figure 1 TRL and CRI mapped on the Technology Development Chain

For a technology to secure a sustainable development path through the demonstration and initial deployment phase it must create a virtuous circle whereby demonstrable potential for improving cost competitiveness attracts sufficient investment to deliver sufficient volume to generate learning. This in turn further improves the technology leading to further cost reduction, further volume, further learning and so on until the technology achieves Commercial Readiness. New technologies often fail to navigate this transition due to a virtuous circle which is why this phase is often referred to as the ‘valley of death’.

The CRI encompasses this ‘valley of death’, with the highest index level being achieved when the technology is being commercially deployed as a bankable asset class. At this stage the technology can be considered to be Commercially Mature. Continued technology development and cost reduction occurs once the technology has become commercially mature as volume itself becomes the predominant driver of cost reduction, rather than merely an indicator of progress.

4 Market status

The global nature of the floating wind market was highlighted in The Crown Estate’s 2012 report[3] on the commercialisation potential of the floating offshore wind industry. Updating this work, we see (Table 1 overleaf), a significant number of other floating wind concepts have been proposed and many are being actively developed.

[2] ARENA - Commercial Readiness Index for Renewable Energy Sectors. Online at http://arena.gov.au/files/2014/02/Commercial-Readiness-Index.pdf (accessed 15/6/2015)

[3] The Crown Estate – UK Market Potential and Technology Assessment for floating offshore wind power. An assessment of the commercialization potential of the floating offshore wind industry (2012). Online at http://www.thecrownestate.co.uk/media/5537/km-in-gt-tech-122012-uk-market-potential-and-technology-assessment-for-floating-wind-power.pdf (accessed 15/6/2015)

Most of the concepts identified have been proposed to utilise standard offshore wind turbines installed as arrays of individual turbines, with the innovation contained within the design and installation of the support structures which can be broadly categorised as **spars**, **semi-submersibles** or **Tension Leg Platforms (TLP's)**. Some concepts are more radical considering multiple turbines per support structure or vertical axis wind turbines.

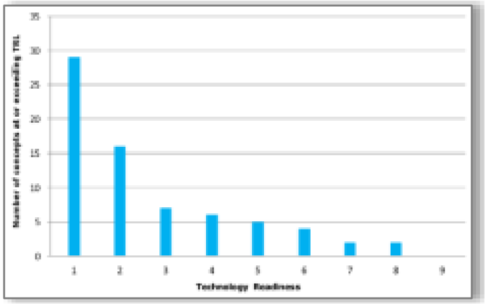

Table 1 Number of concepts at or exceeding given TRL

Despite the fact that an earlier stage concept may prove to be more cost effective in the longer term, the challenge of moving from early TRL levels across the index is a major technical and financial undertaking, usually taking a number of years to complete. The market leaders in floating wind are therefore quite far ahead of other concepts, with the less developed concepts facing a real challenge to 'catch up'.

5 Recent market developments

The offshore wind market in Europe is leading the world and currently accounts for more than 90% of the 8 GW of installed capacity globally. This leading position has extended into floating technology with Statoil's Hywind being the first full scale floating wind deployment in 2009, followed two years later by the WindFloat demonstration project installed off the coast of Portugal. The US has shown significant interest in floating wind, with the first grid connected offshore wind turbine on a floating foundation (although only at 1:8th scale). Japan's energy policy conditions and the depth of much of the continental shelf have led Japan to actively pursue the floating wind market.

5.1 Leading technologies

The leading three device concepts as identified in the previous Crown Estate research carried out by DNV GL are now progressing towards potential deployment:

- Spar buoy being developed by Statoil as Hywind
- Semi-submersible being developed by Principle Power as WindFloat
- Tension Leg Platform being developed by Glosten Associates as PelaStar

An independent assessment provided by DNV GL provide an update on the status of each of these leading concepts

5.2 Hywind

Figure 2 Hywind tow from Åmøyfjorden to Karmøy (2009)

Hywind is a spar buoy concept developed by Statoil. In 2009, following eight years of development work, the 2MW prototype was commissioned. The unit is still up and running as of February 2015, and had a capacity factor of 50% in 2011. This prototype demonstrates that the concept is at TRL 8.

The Hywind concept is now being further developed; Statoil is planning a floating offshore pilot wind farm at Buchan Deep, east of Peterhead on the east coast of Scotland. The pilot park will consist of 5 x 6MW turbines. The project is planned to be in operation in 2018.

Although an inherently stable and relatively simple structure, the large draft may limit construction inshore in many markets. Maintenance is planned to be performed offshore, although if required the structure can be released from the anchoring lines and towed to shore for necessary repair or maintenance. Tow-back in the upended (vertical) position requires deep water depth and deep water maintenance area (e.g. circa >80m).

5.3 WindFloat

Figure 3 WindFloat Installation in Portugal (Source: http://www.marineitech.com/)

WindFloat is owned by Principle Power Inc and is a semi- submersible, three column floater with a single turbine on one of the columns.

In 2011, a Vestas 2MW prototype was installed in Agucadoura, 5km off the Portuguese coast in 40-50 m water depth. This was the first ever full-scale semi-submersible to be deployed, and went from lab scale to full-scale prototype in 30 months. The concept has therefore achieved TRL 8.

Currently, Principle Power is planning for two pilot parks: one 30 MW off the coast of Coos Bay, Oregon, US, supported by the US Department of Energy, and a 27 MW wind farm in Portugal, in partnership with EDP, Repsol and A. Silva Matos. The concept has also been selected for the Kincardine development in Scotland.

WindFloat has shallow draft and the displacement has been stated to be about 5,500 t. It has an asymmetric mooring system with four catenary lines, two mooring lines are placed on column 1 (which carries the turbine) and one on each of the other columns. The substructure has an active ballast system that transfers water between the columns to keep the platform upright as the wind direction changes.

For the 2 MW prototype, a Vestas V80 commercial turbine was used. The only modifications made to the turbine compared to a standard onshore deployment were the use of a wind class 1 tower (stronger) and modified control software. According to Principle Power, the size of the platform is primarily driven by the met-ocean conditions, and not the turbine size. The pre-commercial prototypes are likely to use WTGs in the 3-7 MW range. For the planned demonstration project off the coast of Oregon, Principle Power intends to use 6 MW direct drive Siemens turbines. In May 2014 the USDOE announced that the demonstration project had been selected to receive up to $47m in match grant funding under the Advanced Offshore Wind Programme.[4]

Full assembly, including the turbine, can be done on shore in a suitable dry dock or slipway. For this a large crane must be used. The shallow draft of the structure allows for tow of a fully assembled and commissioned unit. No special vessels are required. The anchors will be pre-laid and ready for mooring of the platform upon arrival to site. Maintenance could be done in a dry dock or at a quay side

5.4 PelaStar

Figure 4 PelaStar (Source Glosten Associates)

The PelaStar concept, developed by Glosten Associates, is a Tension Leg Platform (TLP) structure consisting of an upper hull crossing the water surface and a lower hull with tendons arms that remain submerged. The substructure is made of steel. For the baseline design the displacement of the structure under operation is approximately 4000 tonnes and the draft is 30m, although the demonstrator planned for the Wave Hub site had a higher displacement (5000 tonnes) and lower draft (22m).[5]

It is expected that the substructure steel weight per MW will be lower than the spar buoy or semi-submersible concepts on the market today.

The anchoring solution will require high vertical load anchors due to the tension load in the tendons. Glosten plans to pre-install the anchors, giving them connectors that will allow for tendon hook-up.

[4] http://www.principlepowerinc.com/news/press_PPI_DOE_DSLCT.html
[5] http://www.eti.co.uk/wp-content/uploads/2014/03/PelaStar-LCOE-Paper-21-Jan-2014.pdf

The mooring tendons will be installed when the substructure is installed. The tendons will be dimensioned to allow for replacement of one tendon without compromising the stability.

The concept allows full quayside assembly due to the much lower ‘floating’ draft of 9-12m (the draft is much reduced when the structure is not under tension as the weight is only 30-40% of the operational displacement). The fully assembled floating structure and wind turbine is towed to site and installed using tugs and a special installation barge. It is assumed by the developer that installation could be performed in up to 2.5 m wave heights.

This concept is considered to be at TRL 4-5, with a FEED study complete, tank tests and optimisation studies undertaken and a cost of energy model developed.

5.5 Ongoing global projects

- **IDEOL**: In June 2014 seven European partners, including IDEOL, kicked off the FloatGen demonstration project that aims to deploy a 2 MW floating design based on IDEOLs concept. In late 2013 it was announced that French renewables developer Quadran plans to team up with IDEOL with the aim of building 500 MW farm of offshore wind farms off France by 2020.
- **WindFloat Pacific Project (WFP)**: Principle Power and its partners are planning for a 30 MW floating offshore wind project off the coast of Coos Bay, Oregon. The project will consist of five WindFloat floating foundations equipped with 6 MW turbines. It will be the first offshore wind farm off the West Coast of the United States and is an awardee of the US Department of Energy’s Offshore Wind – Advanced Technology Demonstration program
- **VolturnUS**: VolturnUS is developed by the University of Maine (UoM) and was the first grid-connected offshore turbine to be deployed off the coast of North America. The demonstration project is in a 1:8th scale and UoM have been awarded a $3 million USD award from DOE to assist completion of a full scale design, carrying a 6 MW turbine. UoM is planning for a 2 unit demonstration park with a total capacity of 12 MW in 95 metres of water depth.
- **Scotland:**
  - Kincardine Offshore Windfarm Limited (KOWL) is a proposed demonstrator floating wind farm with an installed capacity of up to 50 MW. The development site is located to the south east of Aberdeen, approximately eight miles from the Scottish coastline. The development is considered a commercial demonstrator site, which will utilise floating semi-submersible technology to install approximately eight wind turbine generators (WTG) in approximately 60 to 80 m of water. As a demonstrator site a final device type has not been confirmed.
  - Highlands and Islands Enterprise (HIE) is progressing proposals for a floating offshore wind test facility known as the Dounreay Floating Offshore Wind Deployment Centre (DFOWDC). DFOWDC plans to provide a test and demonstration test and demonstration

site up to 30MW in a real sea environment to test prototype floating offshore wind technologies. As a demonstrator site a final device type has not been confirmed.

- **GOTO FOWT** – a 2MW Hitachi turbine was installed on a spar buoy near Kabashima Island in 2012

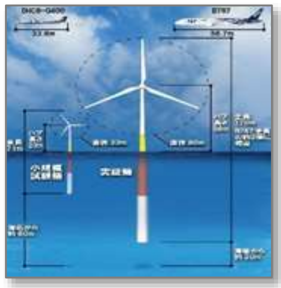

Figure 5 Goto Island FOWT (Source http://goto-fowt.go.jp/english/home/spec/)

- **Fukushima FORWARD project** – in 2014 a 2MW Mitsui Semisubmersible and floating transformer station based on the "advanced spar buoy" technology were installed. This is expected to be followed by a 7MW Mitsubishi Sea Angel in 2015.

Figure 6 Mitsui semi (source: http://www.hitachi.com/New/cnews/131111c.pdf)

6 Technical Challenges

The study characterises the current Status Summary Level of floating wind as CRI2 "Commercial Trial" indicating that, overall, the transition from technology readiness to commercial readiness is lagging many of the indicators. Should more than one of the proposed demonstration arrays go ahead and prove successful the summary level would rapidly move to CRI3 "Commercial Scale Up".

6.1 Technical Challenges

A key aspect of the engagement with stakeholders was to conduct interviews with floating offshore wind technology developers. The key technical challenges that are common across floating structure designs, identified through this consultation, were used as the basis for the formulation of the key technical challenges summarised in table 2. The challenges have been categorised as those relating to the wind turbine, support structure, moorings and anchors, electrical infrastructure, installation and maintenance, and design standards and tools. Mitigating actions that will address each of these challenges have been identified and are also outlined in the table.

Category	Technical Challenge	Mitigation
Turbine	Currently available turbines are adapted from designs for use on fixed structures. There is a need to develop turbine designs specifically for use on floating structures,	Challenge design limits through engagement with turbine and component designers and manufacturers. Better understanding of cost-benefit of improvements,

	with particular emphasis on; • Design limits for rotation and acceleration of rotor nacelle assembly. • Sufficient and appropriate control systems	taking in to account complete system (turbine and support structure). Encourage collaboration between wind turbine designers and floating support structure designers to ensure optimisation.
Support Structure	The support structures for current demonstration projects have not been fully optimised so do not demonstrate the potential for cost reduction from floating wind.	Future demonstration projects should demonstrate the potential for cost reduction through optimisation, using learning from early projects to improve next generation designs.
	The relationship between turbine rating and platform size is not fully understood leading to difficulty in determining the optimum turbine and structure combination.	Develop understanding of relationship between turbine size and support structure through optimisation of designs and learning from demonstration projects.
	Fatigue design of structure and components is poorly understood due to lack of operational experience leading to conservatism in designs.	Improvements to design tools/ methodologies and learning from monitoring and measurement of demonstration projects.
	Yards with manufacturing capability are not equipped for serial production leading to uncertain cost reduction potential in manufacturing.	Investigate how streamlined manufacturing can reduce costs
Moorings and Anchors	Poor understanding of the dynamic behaviour of moorings, particularly for shallow water (40 – 60m) leading to suboptimal mooring design.	Desk based and experimental testing and research in to the behaviour of mooring systems, with a focus on shallow water depths (40 – 60m). Engagement with oil and gas industry to understand how existing techniques can be adapted and lessons implemented.
	Cost of anchors and their installation is high	Investigation in to innovative anchor systems/ shared anchor points
	Large footprint for spread mooring systems creates potential for conflict with other operators in vicinity of installation	Engagement with relevant stakeholders to fully understand risks and mitigations to minimise risk to floating wind components and impact on other marine activities.
	TLP anchor performance is sensitive to soil conditions so increases risk and cost of installation	Development of robust anchoring systems and installation techniques. Development of understanding of geotechnical investigation requirements.
Electrical Infrastructure	Lack of experience with dynamic power cables leading to conservative design	Research in to, and testing of, power cables subject to dynamic loading
	Lack of experience with substations on floating structures	Qualification of electrical components for use on floating structures, in particular for the inclinations and accelerations that they would be subject to.
Installation and Maintenance	Lack of consensus on best approach to installation, e.g. use of special purpose or multi-purpose vessels.	Innovation focused on installation systems. Research in to the design of turbines and support structures for installation.
	Distance from shore and harsh environmental conditions limit availability for inspection and maintenance	Investigate and develop remote inspection and maintenance systems.
Design Standards and Tools	Lack of installation and operational experience means that design drivers are poorly understood so designs may be conservative	Focus on better understanding of design drivers in demonstration projects, including analysis of observed behaviour and feedback to design
	Target safety levels (probability of failure) in design standards are not reflective of risk profile of floating wind, potentially leading to conservative design	Review of target safety levels in design standards to reflect risk profile of floating offshore wind, in particular with respect to quantity of hydrocarbons and unmanned status of structures.

	Software tools that simulate the whole system behaviour are not fully developed or validated.	Demonstration projects and scale tests should be required to deliver high quality measurements for validation of design tools.

Table 2 Technology Challenges

A number of themes are clear in the challenges and their mitigations. Collaboration across the industry and supply chain is key, along with cooperation with other industries, in particular oil and gas, while recognising key differences in risk and cost drivers. Ensuring that demonstration projects are conducted in a timely manner, with appropriate systems to enable learning and best practice development, will support all aspects of the designs being optimised. Targeted research and innovation on aspects of designs that are not core to the IP of technology developers will allow research effort and resource to be effectively leveraged for maximum benefit to the entire industry. It is clear that with appropriately targeted interventions, all of these challenges can be addressed to accelerate development and support cost reduction for floating offshore wind.

7 Conclusions

With more demonstrator projects coming forward, the floating wind sector has seen a lot of progress since the last review was completed in 2012, increasingly becoming a global proposition with the number of technologies entering the sector having grown considerably. Despite these developments it is still an emerging sector, with a number of key milestones to be achieved in order to be seen to be commercially ready.

Through a review of the trends and research, along with industry and stakeholder engagement a number of key conclusions have emerged

1. **Metrics:** Commercial maturity can be seen to be a combination of two crucial indicators, Technology Readiness Levels and the Commercial Readiness Index. As devices reach the highest level of TRL 9 at the demonstration stage they can then progress along the path to commercial readiness. At CRI6 floating wind as an asset class would be considered as “bankable” with market and technology risks no longer driving investment decisions.

2. **Technology status:** There are a large number of floating wind concepts being developed, most of which are at a relatively early stage of development, currently standing somewhere in the range TRL 0-6. This group contains many concepts which are technically more radical than the leading concepts, offering the potential for a more “disruptive” maturation path. The most advanced floating wind technologies are currently at TRL8, with the first multi-unit demonstration projects for these devices at advanced stages of planning. Successful installation of these projects will imply that that these concepts have reached TRL9.

3. **Technical Challenges:** For the floating wind industry to become commercially viable, not only the technical feasibility needs to be proven but also the industry's ability to reduce costs. Much of the cost reduction can be derived from technical advancements which can be addressed through targeted investments and initiatives, both in terms of engineering design and philosophies.

4. **Collaboration:** The industry assessment has identified a number of areas for collaboration. The ability to reduce costs and address the common challenges facing the floating wind industry requires a collaborative approach from technology and site developers. Technology solutions and efficiencies from the supply chain associated with advancing the sector towards commercial readiness require that there is a sufficient market generated through collaborative projects.

5. **Industry Engagement:** In order to better understand industry's current views and approach on floating wind, their assessment of the TRL and CRI levels of various technologies, and to explore opportunities for further engagement, a series of detailed discussions and workshops is recommended. These workshops should involve the turbine manufacturers, suppliers, and offshore wind farm developers.

Credits

This paper summarises findings from research and stakeholder interviews carried out by DNV GL. We would like to thank the team at DNV GL for their support and professionalism in the delivery of this project.

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