Far from shore floating wind farms and associated emerging technologies

Introduction

In June 2015 the Carbon Trust report to the Scottish Parliament[1] identified that the UK would require up to 55GW of wind energy by 2050 and that it would be necessary to move to deeper offshore waters to meet this goal. The move to deeper water requires new design for turbine monopile to be developed since those used in the present round of inshore windfarms will not be suitable in deeper waters. This briefing note explores some of the design options available to achieve this. It also provides some thoughts on the methods for transfer of the energy to the various end users onshore.

Floating Wind Turbine Generator Foundation Concepts

In 2015 Simen Moxnes of Statoil, now Equinor, presented a view of the future of floating wind turbine generators (WTG) to the Offshore Engineering Society (OES)[2]. Within the basic concepts several variations were considered:

- Spar Buoys (HyWind; Njord; HiPRWIND; Sasebo; Nautica AFT and Deepwind);
- Semi-submersibles (Windfloat; WinFlo; WindSea and Vertwind);
- Tension Leg Floaters (DiWET; MES; PelaStar and NREL);
- Hybrid Spar Buoy/Tension Leg Floater (Sway).

The basis of the review was Statoil's HyWind concept[3] which comprises a ballasted cylinder with weighted catenary moorings attached below the water line. The foundation supports a horizontal axis turbine as shown in Figure 1a. Other Spar Buoy concepts use moorings attached at various elevations on the spar, including above water level, variable spar diameters and a vertical axis turbine.

The semi-submersible concepts in general use a vessel formed of buoyant vertical or near vertical cylindrical columns, normally three or four, connected by a tubular space frame. One or more columns may support a tower and horizontal axis wind turbine. As for oil and gas semi-submersibles the structure is anchored by catenary moorings. Figure 1b shows a typical configuration.

Tension Leg Floaters (TLF) use a buoyant column with outriggers at the base to which are attached vertical tension tethers anchoring the structure to the sea floor. Roll stiffness is provided by the spacing of the tethers thereby avoiding the need for a deep structure. Figure 1c shows the configuration of the PelaStar concept.

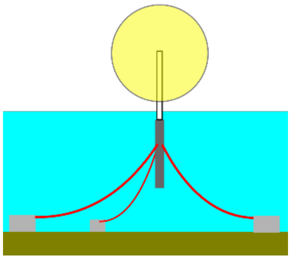		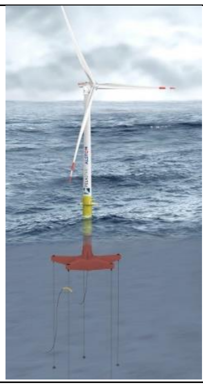
1a: Catenary moored spar buoy (Wikipedia)	1b: Semi-Submersible (Windfloat)	1c: Tension Leg Floater (PelaStar)

Figure 1: Various design options for turbine monopiles in deeper water

Statoil carried out a review of the options using their extensive experience of offshore oil and gas developments, including many floating installations. The review looked at the construction, installation, and operation of the various concepts. A seven-stage ranking system was employed which demonstrated the HyWind concept to be best for their purposes. In 2009 Statoil installed a single 2.3MW WTG off the coast of Norway called Hywind-Demo. This demonstration structure was used to validate the analytical studies on the concept models.

Statoil commenced construction of HyWind Scotland Pilot Park in 2016 with 5 WTGs each of 6MW capacity in a water depth range of 95 to 120m. The wind park is in the Buchan Deep 29kms east of Peterhead and was commissioned in October 2017. In January 2019 Anton Slozkin of Saipem Ltd made a presentation to the OES on the assembly and transport of these WTGs prior to single piece installation[4]. The mating was carried out using the semi-submersible crane vessel (SSCV) the Saipem S7000 in a Norwegian fjord at Stord. For a much larger number of turbines a production line approach could be adopted and use of the large SSCV avoided by a purpose-built facility.

Equinor now propose to develop wind farms with turbines approaching 9MW capacity and a significantly greater number of WTGs. One possible site is the Canary Islands[5]. Significant procurement, fabrication, assembly and installation efficiencies are expected due to scaling.

An advantage of floating wind turbines over monopiles is that a generic design rather than individual design of each WTG may be used to meet dynamic response requirements. It is a requirement that the natural frequency of a WTG avoids both the rotor frequency range (1P) and the frequency of a blade shielding the tower (3P for a 3 bladed WTG)[6,7]. For monopiles and other fixed structures, variations in soil conditions, bathymetry and other factors between individual WTGs impacts on the natural frequency of each WTG. This can require each WTG to be designed individually or in groups, delaying the design completion. For floating structures, the bathymetry, geotechnical and other conditions can normally be regarded as similar for all WTG's within a farm. Adjusting tether configurations and ballast may fine tune the response to ensure consistency of dynamic behaviour. A single WTG design gives opportunities for a production line construction approach and allows earlier procurement of the WTGs.

Whilst Equinor are leading the way with their floating WTG developments, other operators around the world are continuing with their own floating WTG designs to suit particular locations. There will no doubt be design features that prove optimum and thus opportunities exist for design standardisation leading to cost reductions.

A major advantage for floating WTGs is that they can be deployed in water depths in which it is impractical to use a fixed structure. The UK and Norway are well suited to far from shore deeper water developments in the North Sea. As well as the designs in Figure 1 there is potential to reuse decommissioned oil and gas platforms, particularly those where the concrete substructures have been left in place, as hubs for offshore wind farms. Shell's recently or about to be decommissioned Brent Condeep and Seatank platforms are candidates, with each structure able to support a deck weighing over 20,000 tonnes.

Maintenance of North Sea FFSWFs

The maintenance strategy for North Sea Far from Shore Wind Farms (FFSWF) will benefit from the infrastructure developed to support oil and gas installations. A personnel presence, full time or part time, in the wind farm may be required for in-field maintenance. This may be reduced by remote monitoring systems and designs that have long maintenance intervals. An advantage of the floating WTGs is that the farm can be designed such that individual WTGs can be disconnected and returned to an inshore location, with suitable water depth, such as the Norwegian fjords, for major maintenance.

In-Field Energy Transmission

The in-field cabling and riser systems will continue to operate on alternating current (AC) but will need to accommodate greater water depths, the need for catenaries and ability to accommodate dynamic response of the system. This will already have been addressed by the HyWind Project but may require further design development for harsher environments at far from shore locations potentially leading to greater costs. A major issue for FFSWF is the method used to transport the energy generated from a hub back to the shore. There are several ways this could be done:

- Electrical
  - transmission via High Voltage Direct Current (HVDC) subsea cable;
- Hydrogen
  - Transport by pipeline;
  - High pressure transport by ship or container;
  - Liquefied transport by ship;
  - Ammonia transport via pipeline;
  - Ammonia transport by ship.

Options for Energy Transmission to Shore

Electrical transmission from near shore wind farms (NSWF) is normally done using high voltage alternating currents (HVAC). However, as transmission distances approach 100 miles this option becomes less practical and HVDC systems may be required. HVDC systems require considerably larger and more costly offshore transformer and converter substations. Additionally, the cost of the cables to shore will rise in proportion to their length and an onshore station will be required to transform the current from DC to AC for connection to the grid. For DC, interconnector cable voltages of up to 550kv are available but the most common voltage for offshore renewables is 320 kV, as used by the German company TenneT on the BorWin3 project.

For a NSWF the cost of the in-field connectors and the export cable is typically 10% of the total project cost. Recently the cabling costs for the in-field lines have reduced overall for a given offshore output, due to the deployment of larger turbines, necessitating fewer connections, and an increase from 33kV to 66 kV for transmission voltages. It is expected that for deeper waters and dynamic riser systems for in-field cables, the costs will increase for the in-field cabling solution. In addition, the use of electric cables is not without a carbon footprint. The mining, refining and transport of the conductor, copper and aluminium, and polymeric materials in the cables and transformers currently generates green-house gas emissions (GHGE).

Hydrogen as an energy vector and its transfer to shore

All the remaining energy transport options identified are based on hydrogen, which as an energy vector has the advantage over electricity that it is also a means of storing energy. The methods for using hydrogen for energy transport to shore will depend on the end use. China and Japan are developing their national energy strategies based on hydrogen[8]. Their strategies cover several forms of transport (trains, cars, trucks, fork-lift trucks, ships and even air), residential and commercial heating, industrial plant and energy storage for the electrical grid and for local applications.

For rail transport Germany is adding 80 Hydrogen Fuel Cell (HFC) trains to its network[9] and in the UK there are plans to convert existing diesel-electric trains to HFC. For road transport HFC for electric vehicles (HFCEV) are easily integrated into existing infrastructure. Manufacturers such as Toyota[10], Honda, Hyundai, Mercedes and several Chinese manufacturers are producing HFCEV cars, in relatively large numbers, that can refuel in a few minutes alongside Internal Combustion Engine (ICE) vehicles[11] and have ranges consistent with existing ICE vehicles. HFC trucks have been developed with a 1200 kms range[12]. For these vehicles, hydrogen is used in tanks designed for 350 bar or 700 bar. The onshore hydrogen distribution system for these vehicles would favour the transport of the gas from the FFSWF at high pressure to multiple locations, thus favouring the use of high pressure hydrogen containers or ships. The former could be filled on the wind farm's hub platform and launched to the sea for towing to multiple destinations by tugs, either singly or in multiples. Ships would probably be filled at a single anchor leg mooring (SALM), near the hub.

Hydrogen is an effective means for decarbonising the heating systems in 80% of the UK's existing 27 million residential properties and many commercial and industrial properties by replacing methane in the gas main with hydrogen or by diluting it. The H21 Leeds City Gate project demonstrated the commercial and technical viability of introducing 100% hydrogen in the city's gas supply[13]. The Iron Mains Replacement Programme (IMRP)[14], an ongoing upgrade of the national gas main, due for completion in 2032, will be able to accommodate hydrogen. In this case transport to shore of hydrogen from a FFSWF is to specific destinations at lower pressures and favours a pipeline system.

Due to the variability of electrical demand there are numerous occasions when the National Grid is unable to accept all the wind energy generated but this energy still has to be paid for. Ørsted has recently proposed to generate green hydrogen from offshore wind in its Holland Coast 3&4 tender[15], although for this near shore development the hydrogen generation plant will be on-shore. Surplus energy stored as hydrogen can cover peaks in electrical demand through the use of HFC. Substantial hydrogen storage potential exists within the national gas distribution pipework.
The transport of hydrogen from the FFSWF through a pipeline, probably polyethylene, either as a homogeneous pipeline or as a liner for a composite pipe, can take advantage of oil and gas experience. It is

unlikely existing pipelines can be used as those covering a long distance support many existing and future gas installations and are unlikely to be decommissioned. Furthermore, the existing pipelines will require metallurgical control and it will be challenging to demonstrate that these requirements can be met.

Rafael d'Amore-Domenech identified the Southern Ocean has the greatest wind energy density on earth[16, 17]. He concluded that for very long-distance transport of hydrogen, liquefaction was better than compression. The energy losses due to the change of phase can be mitigated by savings in the energy used for transport. Japan is looking to establish an international hydrogen supply network, including Australia and Saudi Arabia. Kawasaki industries are designing a ship for the large volume transport of cryogenic hydrogen at -253°C, shrinking it to 1/800th of its original volume. For comparison LNG carriers to the UK operate at -162°C. A major cost for use at a FFSWF will be the equipment for cryogenic transfer able to operate in severe environmental conditions.

An alternative to transporting hydrogen at low pressure, high pressure or in liquid form is to combine it with nitrogen to form ammonia by the Haber process. It is much easier to transport liquid ammonia in pipelines at relatively low pressures of up to ten atmospheres (than to transport gaseous or liquid hydrogen). Once at its destination the ammonia can be converted back to nitrogen and hydrogen relatively easily. Companies in Australia are examining the potential for storing and transporting renewable energy to overseas customers by this method[18]. The big question is: can the onshore plant be designed to fit on an offshore installation with acceptable capital and operational costs?

Once created the ammonia may be transported in liquid form either through a pipeline or via vessel. A Russian-Ukrainian pipeline from Togliatti to Odessa on the Black Sea is over 2000 kms long and the Magellan pipeline in the USA is in excess of 1760 kms long. Clearly distance is not an issue. One issue with ammonia is its ability to cause stress corrosion cracking (SCC) in the steel. SCC occurs where there is some oxygen (0.5 ppm appears to be sufficient) and a very low water content, if the water content is increased marginally to about 0.2% it mitigates the risk. Using a decommissioned hydrocarbon pipeline for the transportation of ammonia appears practicable. Crolius has examined ammonia to hydrogen conversion at fuelling stations[19].

Another alternative would be to export the ammonia from a FFSWF by vessel. This could be done by piping the ammonia to a SALM for loading. The loading system and vessel for transporting ammonia will be much simpler than those used for transporting high pressure or liquid hydrogen, although some refrigeration will be required.

Conclusions

The development of the floating WTG structures has now reached a level where they can be commercially exploited. However, to harvest the energy of the wind far from shore there is still substantial work to be carried out on the engineering details and the potential project costs of the WTGs to operate in extreme conditions and in the energy transmission to shore. Any assessment must look not only at the generation but all aspects of the transfer of the energy to the various end users. The primary drivers for commercial decisions will include: the energy transport distances; user locations, end user requirements and environmental conditions. The future for floating offshore wind far from shore looks exciting and has great potential for development to assist in meeting the goal of decarbonising our energy supply.

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References

1 Carbon Trust, Floating offshore wind – Market and technology review for the Scottish Government, June 2015.

2 Simen Moxnes, Chief Engineer – Platform Technology Statoil, Floating Wind Turbine Generators, OES meeting, 8th April 2015. https://vimeo.com/icegroup/review/125811203/24bdc2af89

3 Equinor – the world's leading floating offshore wind developer. Viewed 27th May 2019. https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html,

4 Anton Slozkin, Saipem Ltd., Installation of a Wind Turbine Generator onto Floating Foundation, OES meeting, January 2019. https://www.ice.org.uk/eventarchive/installation-of-a-wind-turbine-generator-london

5 Laxman Pai, Offshore Engineer, "Equinor Eyes Floating OWF in Canary Islands", 5th June 2019, https://www.oedigital.com/news/466920-equinor-eyes-floating-owf-in-canary-islands?utm_source=AOGDigital-ENews-2019-06-05&utm_medium=email&utm_campaign=OEGDigital-ENews

6 S. Bhattacharya, Design of foundations for offshore wind turbines, pub. Wiley, 7th May 2019.

7 S. Bhattacharya, Design of foundations for offshore wind turbines. OES meeting, 2nd October 2013. https://vimeo.com/icegroup/review/76334617/e39acc1553

8 M Nagashima, "Japan's hydrogen strategy and economic and geopolitical implications", pub. ifri, October 2018.

9 Alstom, "Alstom Presents hydrogen train in six federal states of Germany", 23rd January 2019. https://www.alstom.com/press-releases-news/2019/1/alstom-presents-hydrogen-train-six-federal-states-germany

10 Toyota, "2019 Toyota Mirai fuel cell electric vehicle", viewed 27th May 2019, https://ssl.toyota.com/mirai/fcv.html

11 ITM, New Shell hydrogen fuelling station opened at Beaconsfield, viewed 27th May 2019, http://www.itm-power.com/news-item/new-shell-fuelling-station-opened-at-beaconsfield

12 Forbes, Startup Nikola bets hydrogen will finally break through with big rigs, 14th April 2019. https://www.forbes.com/sites/alanohnsman/2019/04/14/can-a-15-billion-bet-on-fuel-cell-big-rigs-be-a-game-changer-for-hydrogen/

13 Northern Gas Networks and others, "Leeds City Gate H21 Project report", July 2016

14 Energy World, "Britain's Gas Mains Replacement Programme", April 2018.

15 **FuelCellWorks, "Ørsted Working to Establish Green Hydrogen from Dutch Offshore Wind Farms", 14th March 2019. https://fuelcellsworks.com/news/orsted-working-to-establish-green-hydrogen-from-dutch-offshore-wind-farms/**

16 R. d'Amore-Domenech, Universidad Politécnica de Madrid, "The future of marine renewables: Green hydrogen production at sea", Presented to the Society of Naval Architects and Marine Engineers, London, 17th April 2018.

17 R. d'Amore-Domenech and T J Leo, Universidad Politécnica de Madrid, "Sustainable hydrogen production from offshore marine renewable farms: Techno-energetic insight on seawater electrolysis technologies", pub. American Chemical Society, Sustainable Chemistry & Engineering, 2019,7, 8006-8022

18 Robert F. Service, "Ammonia – a renewable fuel made from sun, air and water – could power the globe without carbon", Science, AAAS, 12th July 2018. https://www.sciencemag.org/news/2018/07/ammonia-renewable-fuel-made-sun-air-and-water-could-power-globe-without-carbon

19 Stephen Crolius, "Progress toward Ammonia-to-Hydrogen Conversion at H2 Fuelling stations", Ammonia energy", 5th October 2017. https://www.ammoniaenergy.org/progress-toward-ammonia-to-hydrogen-conversion-at-h2-fueling-stations/