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18th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS
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VOLUME 2

COMMITTEE V.4

OFFSHORE RENEWABLE ENERGY

COMMITTEE MANDATE

Concern for load analysis and structural design of offshore renewable energy devices. Attention shall be given to the interaction between the load and structural response of fixed and floating installations, taking due consideration of the stochastic nature of the ocean environment.

COMMITTEE MEMBERS

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Chae Whan Rim
Jaideep Sirkar
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KEYWORDS

Offshore wind, marine energy, wave power, tidal energy, loading, design, testing, ocean current energy conversion (OCEC), ocean thermal energy conversion (OTEC).

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1 INTRODUCTION

This report of the current committee describes recent activity of the international ship and offshore industry and the researchers that support it, with specific regard to current pertinent issues and trends relating to Offshore Renewable Energy. It is important to remember that the subject area is vast and developing rapidly, and that this report should be seen not only in the context of the entire ISSC 2012 proceedings but also as a continuation of past ISSC reports and complementing more generic IPCC (Lewis *et al.*, 2011, Wiser *et al.*, 2011) and other pertinent reviews. In addition, the committee chose to focus on areas commensurate with the expertise of the committee members to build on the vast knowledge base generated by previous Committee Two V.4 reports (ISSC, 2006, 2009). With this in mind, the present report has focused on offshore wind, which is by far the most technically and commercially developed of all the offshore renewable energy technologies.

In addition to a significant consideration of offshore wind power, this report, whilst updating developments in wave and tidal power, introduces ocean current energy conversion (OCEC) and ocean thermal energy conversion (OTEC), which have received much attention by IPCC and others but are further from commercial development, due mainly to the scale and investment required for concept demonstration.

An important element of ISSC work is to provide an expert opinion on the subject matter reported. Section 6 summarises the main features of the report and makes specific observations on the topics studied, particularly with respect to where further work is needed.

2 OFFSHORE WIND TURBINES

2.1 Summary of Current Activities

2.1.1 Commercial Installations and Wind Farms

Wind technology has come a long way in the past twelve years, from the first 220 kW offshore wind turbine that was built in Nogersund, Sweden in 1990, to the 1 GW London Array wind farm that was launched in March 2011 on the outer Thames estuary in the United Kingdom (Bilgili *et al.*, 2011).

According to the European Wind Energy Association (EWEA, 2011a), by the end of 2010, Belgium, Finland, Germany, Ireland, Norway, and Sweden had joined Denmark, the UK and the Netherlands, leading the global offshore wind capacity to 2,946.2 MW (approximately 0.3 % of the electricity demand in Europe). Major projects were: in Belgium, Belwind Phase 1 (165 MW); in Denmark, Nysted II/Rødsand II (207 MW); in Germany, Alpha Ventus (60 MW); in Sweden, Gässlingegrund (30 MW); and, in the UK, Robin Rigg (180 MW), Gunfleet Sands (172.6 MW), and Thanet (300 MW). The total installed offshore wind power in 2010 was 883 MW, a 51 % increase from 2009 (EWEA, 2011b).

In March 2007, the European Union set a target for 20 % of energy consumed across Europe to come from renewable sources by 2020. This challenging target would entail a total installed capacity of 40 GW of offshore wind power by 2020 and an average annual increase of 28 % (EWEA, 2010). For example, the UK would need to build 29 GW of offshore wind by 2020 to deliver its target of 15 %. This includes the Round 1 and Round 2 developments, with a total of 8 GW offshore wind power currently in operation or under construction, as well as Round 3, with another 21 GW to be installed starting in 2015 (Carbon Trust, 2008).

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China's use of onshore wind power has increased rapidly in recent years, but its development of offshore wind farms has been relatively slow. Per April 2010, the offshore wind development pipeline stands at approximately 11.9 GW, and a total 650 MW capacity of wind power has been installed or is under construction off the coast of China (Qin *et al.*, 2010). The first commercial wind farm, Donghai-Bridge, was completed in February 2010, and is located 10 km offshore near Shanghai, with an average water depth of 10 m (Enslow, 2010). The wind farm consists of 34 3-MW Sinovel wind turbines. The support structure is based on a four-pile concept (Lin *et al.*, 2007).

So far, there is no offshore wind farm installed in Japan. However, the study by Ushiyama *et al.* (2010) suggested a roadmap with a long-term goal of installing 25 GW of offshore wind power by the year 2050. Under this plan, the country would begin construction of fixed offshore wind turbines in 2015 and of floating wind turbines in 2020. The aftermath of Fukushima has contributed renewed emphasis on this project.

By the end of 2010, there were 822 monopile and 295 gravity-base wind turbine structures, out of a total of 1,136 wind turbines in the European offshore wind farms. Though steel monopile and concrete gravity structures were still widely used for water depths up to 25 m, wind farm projects involving jacket, tripile and tripod substructures have been completed in water depths ranging from 30 to 40 m (EWEA, 2011a).

Offshore wind turbines installed today are generally between 2 and 4 MW. The largest turbines used so far at sea have been 5 MW (Bilgili *et al.*, 2011). However, as shown by Snyder and Kaiser (2008), there is a clear trend toward increasing turbine size in offshore projects in order to achieve economies of scale. Larger wind turbines could be used offshore because of the lack of a number of possible constraints, such as aesthetics and noise limitations. On the other hand, designs need to address issues related to marine conditions, corrosion, and reliability (Fichaux *et al.*, 2009).

Offshore wind power remains relatively costly and risky because of the inherent uncertainties and often severity of the marine environment. The biggest concerns in the economics of an offshore wind farm are the construction and installation of the support structures, the connection to the grid, and operation and maintenance (Snyder and Kaiser, 2008, Sørensen, 2009). According to Morthorst *et al.* (2009), typical investment costs of recent offshore wind farms range from € 1.2 to 2.7 million per MW. The cost of support structures (mainly monopile and gravity-base so far) accounts for about 20 % of the total investment cost. For floating wind turbines, the cost is expected to be much higher. However, the cost for support structures is very dependent on the distance to shore and the depth of the water. New designs for substructures and foundations, as well as new installation vessels, are needed to reduce cost (Snyder and Kaiser, 2008, Fichaux *et al.*, 2009).

In terms of operation and maintenance (O&M), two philosophies are emerging to help reduce cost. The first is to limit the risk of failure while developing a simple and robust turbine. The second is to improve wind turbine intelligence and implement redundancy and preventive maintenance algorithms (Fichaux *et al.*, 2009). Under the harsh environmental conditions of wind and waves, access to offshore wind turbines becomes challenging or even impossible for extended periods (Breton and Moe, 2009). Various methods to provide better access under certain conditions are under consideration and development, including inflatable boats or helicopters (Van Bussel and Bierbooms, 2003). Advanced O&M approaches, based on remote assessments of turbine operability and the scheduling of preventative maintenance to maximize access during favourable conditions, are also being investigated and employed (Wiggelinkhuizen *et al.*, 2008).

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It may also be possible to economize by using cables with a capacity slightly less than that of the wind farm. This is because offshore wind farms rarely generate at full capacity (Green and Vasilakos, 2011). Moreover, development plans that take into account interactions between projects and the onshore grid also minimize the cost of connecting offshore wind farms to the grid.

2.1.2 Current Research Activities and Test Sites

Current offshore wind technology has been successfully developed from the onshore wind industry and has resulted in a significant deployment of large wind farms in relatively shallow water (less than $30\,m$). However, in the future, new technology for wind farms in deeper water, especially in terms of support structures, needs to be developed (Michel *et al.*, 2011).

In order to encourage and support the production of wind power further offshore and in deeper water, costs must be reduced. Current research work aims to reduce the average cost per kW by enhancing component reliability, increasing wind turbine size and exploring novel substructures to support large turbines, including floating structures.

In connection with the Beatrice demonstration wind farm in the UK, the DOWNVInD project (Beatrice Wind Farm Website, 2011), funded by the EU Sixth Framework Programme (FP6), was carried out from 2004 to 2008. The project demonstrated the technological feasibility and commercial viability of deploying large offshore wind turbines in deeper water (at a water depth of $40\,m$). Two $5\,MW$ wind turbines were installed on jacket substructures and provided electrical power to the Beatrice platforms. This project also focused on the potential environmental impact of the installation and operation of offshore wind farms. The overall environmental impact was reported to be non-significant by its operators (Talisman Energy (UK) Limited, 2006).

The 2006 – 2011 UpWind project (Fichaux *et al.*, 2011), also funded by the EU FP6, focused on the design of very large wind turbines for both onshore and offshore application. The project team developed design tools for the complete range of turbine components, addressing the aerodynamic, aero-elastic, structural, and material design of rotors. A conceptual wind turbine of $20\,MW$ was designed, although more research needs to be carried out to demonstrate its economic feasibility (Fichaux *et al.*, 2011). Among other topics, the research focused on advanced control systems, aiming to reduce the applied structural loads and improve wind turbine design. The team also studied the design of support structures for offshore turbines, based on fixed solutions. They designed a reference jacket substructure to support a $5\,MW$ wind turbine at a water depth of $50\,m$.

Prototype or small-scale tests of floating wind turbines at sea have been carried out for some of the concepts (Wang *et al.*, 2011), including the HYWIND prototype, the SWAY small-scale model, the Blue H concept, and the WindFloat prototype. The first full-scale spar floating turbine, called HYWIND, was installed by Statoil off the west coast of Norway in September of 2009, at a water depth of $220\,m$. It has been in operation for more than two years (HYWIND Website, 2011). This prototype is equipped with a $2.3\,MW$ Siemens variable speed pitch regulated wind turbine mounted at a deep draft floating buoy. The $5300\,m^3$-displacement hull is moored by three mooring lines consisting of steel wires and clump weights.

Another prototype using the concept of a floating spar filled with ballast was installed by SWAY off the west coast of Norway in March of 2011 (SWAY Website, 2011).

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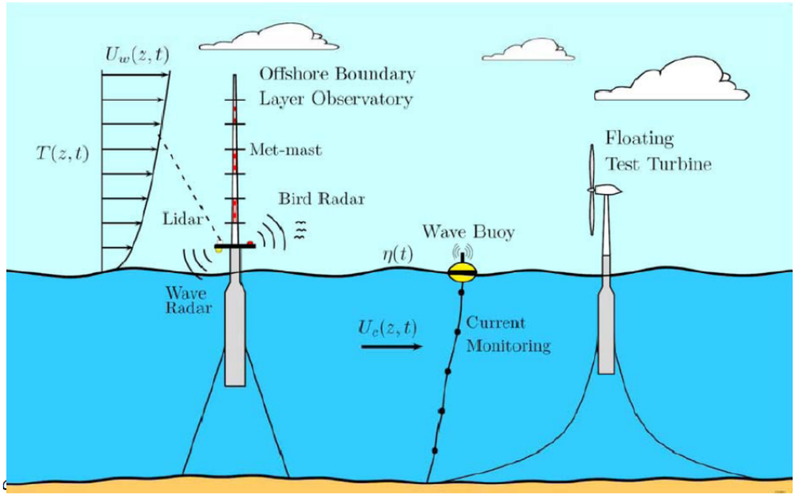

Figure 1: Components of the NOWERI (Reuder, 2011)

Unlike the HYWIND project, in this case, the spar is anchored to the seabed with a single pipe and a suction anchor. This system has the advantage of allowing the wind turbine to revolve naturally as the wind changes direction. An unforeseen sea state condition is reported to have led to its sinking in December 2011. A modified spar which has almost half the draft of a conventional spar was developed by IHIMU (IHI Website, 2011). The concept has ballast and a footing structure with a larger diameter.

A large-scale (3:4) prototype of a tension leg platform (TLP) was installed by Blue H Technologies off the coast of southern Italy in the summer of 2008 (Blue H Website, 2011). The hexagonal floating platform was placed at a water depth of 113 m and fitted with a two-bladed turbine rating 80 kW. The unit was decommissioned after 6 months at sea. A second proof-of-concept prototype, testing a 2 MW wind turbine mounted on a TLP, is expected to be built by 2012 and installed near the site of the future floating wind farm Tricase.

Principle Power Inc. is promoting a semi-submersible floating wind turbine system, called WindFloat, which consists of three columns with patented horizontal water entrapment heave plates at the bases (WindFloat Website, 2011). These structures aim to improve motion performance by using additional damping and entrained water effects. In addition, platform stability would be augmented by a closed-loop active ballast system. A 2 MW version of WindFloat was installed off the shore of Portugal in October 2011.

Recently, there have been developments in the offshore test sites for wind turbines. The Norwegian Offshore Wind Energy Research Infrastructure (NOWERI) is a proposed test infrastructure which consists of an offshore boundary layer observatory and a 250 kW floating test wind turbine, (Reuder, 2011) (see Figure 1). It will be built and testing will start at the beginning of 2013. It will simultaneously measure the environmental conditions of wind, waves, and current, and the dynamic responses of the floater. This can be used to validate numerical tools for floating wind turbines.

2.1.3 Novel Concepts

Future offshore wind turbines may be larger and lighter, and therefore more flexible. Offshore wind turbine size is not restricted in the same way as onshore wind turbines.

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Additionally, the relatively higher cost of offshore substructures provides additional incentive to increase returns by building larger wind turbines (Wiser *et al.*, 2011). However, the development of large turbines for offshore applications involves research challenges, requiring continued advancement in component design and system-level analysis. New concepts, such as vertical axis wind turbines, gearless wind turbines, and other types suitable for large scale development are being considered to design more efficient, more reliable, less expensive, bigger, and easier-to-maintain wind turbines.

The vertical axis wind turbine (VAWT) design is known to work well for small scale wind turbines. However, Risø DTU has proposed the concept of a large floating VAWT, to be created through the 4-year long DeepWind project funded by the EU FP7. The floating VAWT shown in Figure 2 consists of a Darrieus type rotor, a long vertical tube rotating in the water, a generator mounted at the bottom of the tube, and an anchoring system (Vita *et al.*, 2010). Risø DTU has suggested three types of configuration: sea bed configuration, torque arm fixed configuration, and mooring fixed configuration. In the sea bed configuration, the shaft is hinged to the sea bottom so that it can tilt back and forth and to the sides, giving it two degrees of freedom. In the torque arm fixed configuration, a torque arm connects the shaft to the sea bed, so that the turbine system can move up and down in addition to back and forth and side-to-side, allowing it three degrees of freedom. In the mooring fixed configuration, three torque arms installed to the generator box are connected to the sea bottom by mooring lines. This system allows for two more degrees of freedom (sway and surge) than the torque arm fixed configuration. Risø DTU calculated the motions and forces of the sea bed configuration using HAWC2 aero-elastic code (Larsen and Hansen, 2008). The HAWC2 was originally developed to simulate horizontal axis wind turbines (HAWTs) and was modified for VAWTs for the project. The results show a strong coupling between the pitch and roll motions of the system, due to the system's gyro-motion hydrodynamic side force. Another coupling between the aerodynamic and hydrodynamic forces also exists, due to the dependency of hydrodynamic force and friction moment to the rotor's rotational speed. This means that hydrodynamic optimization should be included in the aerodynamic optimization. In addition to these results, Risø DTU found that the hydrodynamic load is dominant in the system's dynamics. They determined the hydrodynamic dominancy using the tilt angle dependency on the current speed and the elliptical tower motion in the equilibrium in waves. Many facts must be

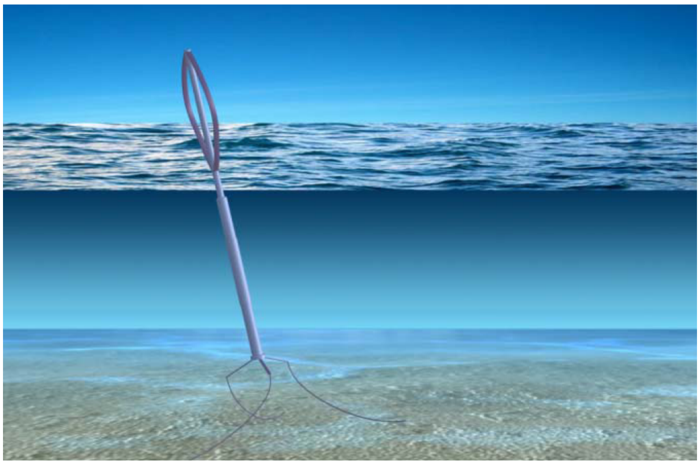

Figure 2: The DeepWind concept (Vita *et al.*, 2010)

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clarified before this concept can be realized. However, it could aid in reducing cost in O&M and installation and increase up-scaling potential and suitability for deep sites.

Another concept for offshore vertical axis wind turbines is the NOVA (Novel Offshore Vertical Axis) concept (Cranfield Website, 2009). This project is funded by the Energy Technology Institute (ETI) in UK. The project aims to have 1 GW of offshore vertical axis turbines installed by 2020. The first phase of the project aims to demonstrate the feasibility of a unique vertical winged wind turbine (an aerogenerator turbine) compared to conventional horizontal axis turbines (see Figure 3).

Simultaneously, Siemens and General Electric (GE) are planning to develop larger low speed generators without gearboxes, to replace traditional gearboxes and high speed generators. This kind of wind turbine is called a "direct-drive" or "gearless" turbine. Since a gearbox is not necessary, a gearless turbine has fewer components and hence reduces maintenance costs over the long term. However, to drive directly, the shaft speed should be the same as the rotor speed, which means that much bigger generators are required, making the generator much heavier than gear type generators. In 2010, Siemens developed a 3 MW gearless wind turbine that uses a permanent magnet generator. In 2011, they developed a 2.3 MW turbine for low to moderate speed (Terra Magnetica Website, 2010). Siemens has also announced that it plans to finish developing a 6 MW gearless wind turbine in 2011 that is suitable for large offshore wind farms (ThomasNet Website, 2011). General Electric acquired a 3.5 MW gearless wind turbine from ScanWind in 2009 (Technology Review Website, 2009) and introduced a 4 MW gearless wind turbine optimized for offshore operation in 2011 (REVE Website, 2011). General Electric is also planning to develop up to 15 MW of direct drive wind turbines using superconducting magnets (Recharge Website, 2012). The superconducting technology could reduce the size and weight of the generator. STX Windpower B.V. also commissioned a 2 MW gearless wind turbine in Korea (Offshore Wind Website, 2011).

Some researchers are exploring very large turbines of more than 10 MW. The UpWind project studied the design limits of upscaling wind turbines (Fichaux *et al.*, 2011). They found that rotor diameters of 20 MW would be around 200 m, compared to about 120 m on today's 5 MW turbines (see Figure 4). The project foresees that the

Figure 3: The Aerogenerator X concept (Courtesy Wind Power Ltd and Grimshaw)

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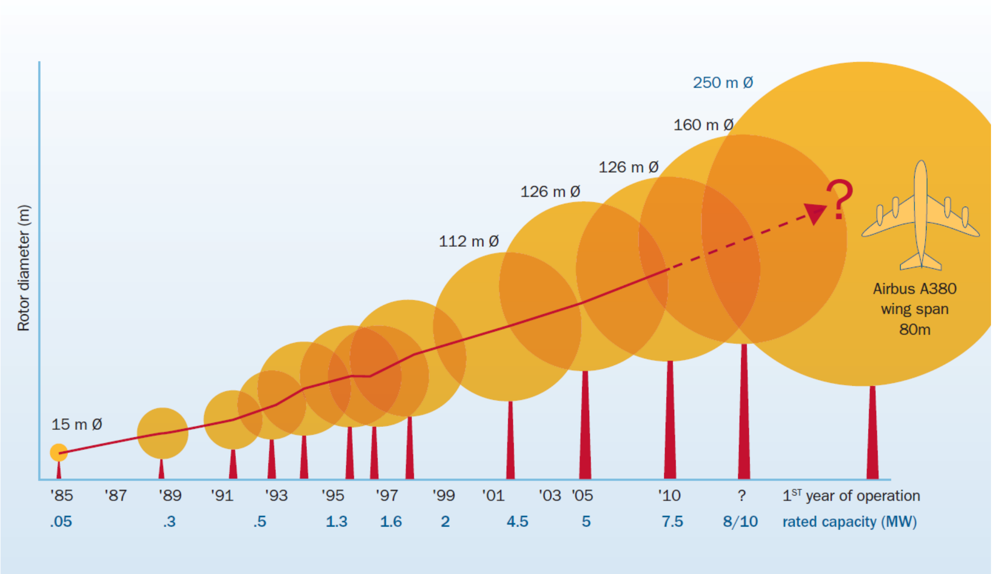

Figure 4: Trend of wind turbine size (Fichaux *et al.*, 2011)

wind turbine up to 20 MW is possible, provided some key innovations are developed and integrated. These innovations include blade material light and strong enough to endure a larger load and a control system incorporating distributed blade control and individual pitch control.

2.2 Fixed Solutions

The 2009 ISSC report introduced various support structures and foundations for offshore fixed wind turbines. These support structures include gravity-base, monopile, tripile, tripod, or jacket, and the foundation solutions are based on piles, gravity bases, or suction buckets (ISSC, 2009).

Currently, offshore wind farms are mainly built in shallow water (less than 30 m of water depth), using monopile or gravity-base support structures. In the next phase of offshore wind development, moderate water depth will be considered and jacket support structures are expected to play an important role for such water depths (Douglas-Westwood Limited, 2010), from 30 m until a water depth at which a floating wind turbine becomes cost-effective.

2.2.1 Jacket Support Structures

Jacket structures are the most common fixed structures used in the offshore oil and gas industry. They have been mainly used for water depths of less than 150 m, but the largest jacket structure was installed in water of 412 m deep (Chakrabarti *et al.*, 2005). However, for offshore wind applications, jacket structures are not considered to be economically feasible at such water depth; they are more suitable for moderate water depths.

In shallow water, monopile or gravity-base structures are the best solution for offshore wind power, due to their simplicity and low cost. When the water depth increases, the overturning moment due to wind loads acting on the rotor increases, and therefore a larger substructure is needed. On the other hand, larger monopiles implies larger wave loads. It is then natural to choose jacket structures that are more “transparent” to

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wave loads. So far, there have been two jacket wind turbines installed on the Beatrice wind farm in the UK since 2007 (Beatrice Wind Farm Website, 2011) and six on the Alpha Ventus wind farm in Germany since 2010 (Alpha Ventus Wind Farm Website, 2011). The turbines on both wind farms are REpower 5 MW machines, and the jacket support structures are designed by OWEC Tower AS in Norway. The water depth is 40 m and 30 m, respectively.

The EU FP6 UpWind project designed a jacket support structure in 50 m water depth, using the NREL 5 MW turbine as a reference wind turbine (Jonkman *et al.*, 2009). This jacket structure is now used as a reference model in the International Energy Agency (IEA) Offshore Code Comparison Collaboration Continuation (OC4) benchmark study (IEA OC4 Website, 2011). A preliminary design of a jacket substructure was also made for a 20 MW wind turbine, which was developed in the UpWind project by scaling the NREL 5 MW turbine. However, the project concludes that more research work on both wind turbine and jacket structure is necessary, in order to achieve a cost-effective design for such large scale wind turbines (Vemula *et al.*, 2010).

Gao *et al.* (2010) analysed a jacket structure for a water depth of 70 m, designed by Aker Solutions ASA for a northern North Sea site. The jacket substructure (including transition piece, jacket, and piles) weighs about 1434 t, while the OWEC jacket on the Alpha Ventus wind farm in 30 m water depth weighs about 825 t (Seidel, 2007). All of these wind turbines have a cylindrical tower and a four-leg jacket, and a transition piece is required to connect them. Truss-tower wind turbines have been proposed by Long and Moe (2007), where the legs and braces extend from the sea bed up to the nacelle.

2.2.2 Design Challenges for Jacket Wind Turbines

The major challenge for offshore wind turbines is finding a cost-effective solution. This challenge must be considered for the turbine's entire lifecycle, including the phases of design, installation, operation, and maintenance. In deeper water, the substructure's contribution to the total cost of an offshore wind turbine increases. As wind turbines becomes standard components, ensuring an optimized and cost-effective substructure design is important to bringing down the total cost. Therefore, this report focuses on the substructure for offshore wind turbines.

As wind turbines become larger (from a rated power of 2 – 3 MW to 5 MW), dynamic loading in the substructure increases significantly. This creates a design challenge for jacket substructure. Aerodynamic loads may excite resonance and induce a high dynamic amplification for jacket responses, and fatigue design of jacket joints and especially welded joints needs to take these effects into account. Moreover, hydrodynamic loads also contribute to fatigue damage. Cast joints could be used, but the fabrication cost of doing so is significantly high.

From a structure point of view, in addition to the jacket and the piles, the transition piece is also an important element for design. Fatigue is also a challenging problem for transition pieces, due to high stress concentration. Moreover, the stiffness of the transition piece will influence the natural frequency of the complete jacket wind turbine and therefore the overall dynamics. So far, limited information has been published on this structural component. Transition pieces based on steel braces were developed by OWEC Tower AS and used in the jacket wind turbines in both the Beatrice and Alpha Ventus wind farms. The transition piece proposed by Rambøll AS (Vemula *et al.*, 2010) is a concrete structure, which is very stiff but quite heavy. The steel cone

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developed by REpower (Seidel, 2007) is much lighter than the other two concepts, but has only been tested for a relatively steep batter angle and a narrow jacket top.

There is limited industrial experience reported so far for jacket wind turbine design. Current design practices deal with the design of wind turbines and jacket substructures separately. The design of the jacket substructure is based on the load information at the interface obtained by aerodynamic analysis from the wind turbine provider. However, due to the coupling of dynamic responses of the wind turbine and support structure, the design process of an offshore wind turbine needs to be carried out in an integrated manner.

The EU FP6 UpWind project proposed and demonstrated an integrated design methodology for the design for a jacket wind turbine in a water depth of $50\,m$ (Fischer and de Vries, 2010). Through this methodology, an optimized substructure design has been achieved to compensate for the variability of sites on a wind farm, and a new wind turbine controller has been developed to actively mitigate the dynamic loads on the support structure. The integrated design method requires coupled analysis tools to address the wind- and wave-induced dynamic responses, which will be discussed in Subsection 2.2.3 under "Coupled Analysis", see page 169.

Currently, the design method for offshore wind turbines is based on the partial safety factor method, which is also used for onshore wind turbines. The reliability-based design is not a common approach so far, but structural reliability analysis methods have been applied to calibrate the load and material factors used in the design method. Tarp-Johansen *et al.* (2003) proposed a calibration method of partial safety factors for extreme loads on onshore wind turbines, that could be further applied to calibrate the safety factors for combined wind and wave load effects for offshore monopile or tripod wind turbines (Tarp-Johansen, 2005). Sørensen (2011) carried out a reliability-based calibration of fatigue safety factors for the jacket substructure developed in the UpWind project. A reliability level corresponding to an annual failure probability of $2 \cdot 10^{-4}$ has been considered, which is normally used for unmanned offshore fixed structures in the oil and gas industry. However, a structural reliability method requires a detailed analysis of uncertainty, and for offshore wind turbines, more experience needs to be gathered to quantify the model uncertainty of the aerodynamic and hydrodynamic load calculation method, the structural dynamic analysis model, and the method for extreme value prediction or fatigue calculation and the statistical uncertainty related to the time-domain simulation.

2.2.3 Dynamic Analysis of Fixed Wind Turbines

Aerodynamics, Hydrodynamics, and Structural Dynamics

The design of offshore fixed wind turbines needs to address the load effects on the structure under environmental forces. Wind and wave loads are the most important of these load sources. The Blade Element Momentum (BEM) theory (Hansen, 2008) is frequently used for aerodynamic load calculation. Using two-dimensional coefficients, the sectional lift and drag forces and the moment are calculated based on the relative wind speed at various positions of the wind turbine blade, which includes the effect of the wind inflow speed, the induced velocity from the momentum theory, and the velocity induced by the motion and deformation of the blade. Engineering corrections (Hansen *et al.*, 2006) are usually applied to deal with the flow conditions that the BEM method is not able to solve, including the Glauert correction for large induction factors, Prandtl's tip loss correction, the dynamic inflow model, the engineering model for yaw or tilt conditions, and the dynamic stall model. The BEM method is still the

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most common tool to obtain the aerodynamic loads on wind turbines, due to its computational efficiency. In recent years, there has been a significant development in more advanced numerical methods (Hansen *et al.*, 2006). This includes the panel method, the vortex method, the generalized actuator disc method, and the Navier-Stokes solvers (full Computational Fluid Dynamics (CFD)). However, the application of the full CFD to rotor aerodynamics is still very time-consuming, and not practical for wind turbine design in the industry.

Hydrodynamic loads on the substructure are also based on a two-dimensional method using Morison's formula, as the typical substructures such as monopile, tripod, and jacket consist of slender members. However, the MacCamy-Fuchs correction is applied on the inertia term of the Morison's formula for structures with a large diameter relative to wave length, such as gravity-base. For wave kinematics, linear waves with the Wheeler stretching model are commonly used for fatigue load analysis. Veldkamp and van der Tempel (2004) compared this model with the second-order wave theory considering irregular waves, and found that the difference in the fatigue loads on a monopile wind turbine is insignificant. However, for this type of wind turbines, the fatigue damage is mainly induced by wind loads. In extreme conditions, the slamming loads due to breaking waves are important to consider, since the aerodynamic damping for such condition is very low. De Ridder *et al.* (2011) carried out an experimental study of breaking wave loads on a monopile wind turbine. Large horizontal acceleration at the nacelle was observed in the order of 0.9 times the gravitational acceleration. CFD has been applied to study such phenomena, e.g. by Bredmose and Jacobsen (2010). However, more work needs to be carried out to implement nonlinear wave theory and slamming load calculation in coupled analysis tools.

In structural dynamic analysis, the complete structure of an offshore wind turbine is normally modelled as beams using the Finite Element Method (FEM), or the multi-body formulation. The geometric nonlinearity due to the rotating blades should be considered for such analysis. Since the wind turbine blades are long and flexible, natural modes of edge-wise and flap-wise bending have low frequency and can be excited by the wind loads. Moreover, due to the large mass of the nacelle and rotors on the top of the tower, the natural frequencies of the first fore-aft and side-to-side bending modes of the complete structure are also low, and these natural modes can be excited by wind loads as well. As an example, for the three-blade NREL 5 MW wind turbine (Jonkman *et al.*, 2009), the lowest natural frequency of the tower plus the rotor is about 0.32 Hz, while the blade natural frequency ranges from 0.67 to 2.02 Hz. It is important to consider the aeroelasticity in the structural analysis for wind turbines.

Design Load Prediction

Both ultimate limit state (ULS) and fatigue limit state (FLS) should be considered for the design of offshore wind turbines. ULS design needs to address the extreme loads or load effects corresponding to a return period of 50 years, see e.g. IEC 61400-3 (IEC, 2009). A full long-term analysis method could be used, which is based on a long-term distribution of responses obtained from the short-term distributions considering the probability of occurrence for all wind and wave conditions. Time-domain response analysis of offshore wind turbines is frequently applied to obtain the short-term distribution, which is further fitted by analytical distributions. Distributions of peak values or extreme values could be considered for each short-term condition. Agarwal and Manuel (2009) have applied this method to study the extreme response of a monopile wind turbine in 20 m of water. To limit the simulation requirement, a response surface

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method is applied to obtain the short-term extreme value distribution as a function of mean wind speed, significant wave height, and spectral peak wave period. An inverse first-order reliability method is used to obtain the characteristic long-term extreme value. However, that study only considers operational conditions, since, for such water depth, the extreme wind turbine response is governed by wind loads, which give the largest thrust force at the rated wind speed due to the blade pitch controller. In deeper water, the contribution of wave loads will increase, and it is therefore important to include all of the load conditions in a full long-term analysis.

Alternatively, contour line (or surface) method can be applied to obtain the long-term extreme response, in which response analysis is carried out for a set of conditions along the environmental contours with a return period of 50 years. Then, the largest extreme response predicted under these conditions, with a proper selection of fractile, is used to approximate the long-term extreme response. This method has been frequently used to predict the long-term wave-induced responses for offshore oil and gas platforms (Winterstein *et al.*, 1993). An important assumption is that the long-term extreme responses are mainly due to the contribution from severe wave conditions. For offshore wind turbines, such assumptions must be checked carefully, since other conditions than extreme wind and wave conditions might give large responses. More research work needs to be done to validate the use of the contour line method for offshore wind turbines.

Since short-term time-domain simulations are normally based on a 10-minute period with several random seeds, when the short-term extreme value distribution is used, an extrapolation method must be applied in order to obtain the extreme value – for example, in 1 hour or 3 hours. Cheng (2002) compared various methods for short-term extreme value prediction and concluded that the peak-over-threshold method and the method based on statistical moments agree well with the reference method using the maximum value directly from simulations.

The current design codes, e.g. GL IV Part 2 (GL, 2005), IEC 61400-3 (IEC, 2009), and DNV OS-J101 (DNV, 2011), require a ULS check for a number of load cases, defined by various environmental conditions of wind, waves, and current, including both operational and extreme conditions with and without faults. This assumes that the 50-year extreme responses are captured by these defined load cases.

Currently, the design of offshore wind turbines with respect to FLS is normally based on the SN-curve approach. Since time-domain dynamic analysis is required, the fatigue loads are extracted directly from the load or stress time history by using the rainflow cycle counting method. For monopile wind turbines in relatively shallow water, design loads are mainly governed by wind loads. For jacket wind turbines, both aerodynamic and hydrodynamic loads need to be considered in the design. However, the relative importance of wind and wave loads is different for ULS design and FLS design. As shown by Cordle *et al.* (2011), both wind and wave loads are important to consider for extreme load cases. However, fatigue loading is found to be dominated by wind, with a relatively low contribution from hydrodynamics. Dong *et al.* (2011) drew a similar conclusion after carrying out a detailed fatigue analysis of joints in a jacket wind turbine of $70\,m$ water depth. They found that the first four bending modes of the complete jacket wind turbine are excited by the wind loads on the rotor, which contributes significantly to the fatigue damage of tubular joints. However, the hydrodynamic response is quasi-static, since the jacket substructure is stiff. Moreover, the wind- and wave-induced responses have different frequency components, which lead the combined stress history to be broad-banded. Therefore, the fatigue damage

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obtained from the combined history is much larger than the summation of the wind- and wave-induced fatigue damages.

Decoupled Analysis

Time-domain simulations of wind- and wave-induced dynamic responses of offshore wind turbines are usually performed using numerical tools. A decoupled analysis calculates the wind- and wave-induced responses separately and uses the summation to obtain the total responses, while in a coupled analysis, both wind and wave loads are applied simultaneously. Considering the large number of load cases, especially in a fatigue design check, decoupled analysis is still needed in practice, due to its computational efficiency. Such methodology is still used in the current design practice in industry, where the designs of wind turbine and jacket substructure are carried out by the turbine provider and the substructure provider, separately, with the exchange of necessary information.

Kühn (2001) has developed a simplified procedure for long-term fatigue analysis of a monopile wind turbine, based on the separate analyses of aerodynamic responses in the time domain and hydrodynamic responses in the frequency domain. Combined fatigue damage is calculated based on a quadratic superposition of separate wind- and wave-induced damages.

In the analysis of tripod wind turbines, Seidel *et al.* (2004) modelled the tripod substructure as a 6-DOF (degree of freedom) system with equivalent mass and stiffness matrices and hydrodynamic loading at the interface. The team performed time-domain simulations based on this equivalent model, using the standard aerodynamic code FLEX 5 (Øye, 1999). They applied a sequential coupling approach using time series of forces or displacements at the interface to analyze the dynamic response in the substructure. In general, they observed a good agreement between the sequential coupling approach and a full coupling approach. However, for jacket wind turbines, they found that this reduction method is not able to capture natural modes at higher frequencies, and the sequential approach over-predicts the responses at these modes (Seidel *et al.*, 2009).

Passon (2010) has compared the equivalent fatigue damage in jacket joints by using the sequential coupling methods with and without consideration of the inertia forces in the jacket structure. The method neglecting the inertia effect underestimates the fatigue damage significantly. He also found that the super-position of separate wind- and wave-induced responses provides accurate estimates of fatigue damages. Moreover, he studied the effect of local joint flexibility, and, found that, in most of cases, the method with no consideration of local joint flexibility overestimates the fatigue damage.

Gao *et al.* (2010) approximated the substructure of a jacket wind turbine with several vertical beams to achieve the equivalence in mass, stiffness and hydrodynamic loading, as well as the first and third bending modes. The sequential method was applied to dynamic response analysis due to wind and wave loads, which gave very similar global responses (e.g. the shear force and bending moment at the sea bed) in the jacket substructure and in the equivalent model. Based on this method, Gao and Moan (2010) carried out a long-term fatigue analysis considering these global responses, and they discussed the contribution of various short-term wind and wave conditions. However, this modelling technique needs to be verified with the fully coupled analysis of a jacket wind turbine, and the effect of torsional modes needs to be addressed.

A proper estimation of damping force is important for a dynamic response analysis of offshore wind turbines. Damping of an offshore fixed wind turbine consists of

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aerodynamic damping, hydrodynamic damping, soil damping, and structural damping. Aerodynamic damping from an operational wind turbine is the most important contribution. For a 3 MW, two-blade, fixed-speed variable pitch wind turbine, Kühn (2001) estimates the aerodynamic damping as from 5 % of the critical damping in low wind speeds to 0.5 % in high wind speeds. However, the aerodynamic damping in the cross-wind direction is very small. Tarp-Johansen *et al.* (2009) have studied soil damping for a monopile foundation using a 3D finite element model, and suggest a damping ratio of 0.55 – 0.8 %. The structural damping provided by the monopile is very small, while that of a jacket structure with welded joints is higher. GL (2005) suggests a total 1 % of the critical damping for extreme wind conditions, in which the turbine is shut down and the aerodynamic damping is negligible.

Coupled Analysis

In a coupled analysis for offshore wind turbines, the aerodynamic loads, the hydrodynamic loads, and the structural responses are dealt with simultaneously in the time domain, as well as in the wind turbine controller. The phases between the wind and wave excitations and the structural responses are properly considered in such analysis, and various types of damping sources, including aerodynamic, hydrodynamic, soil and structural damping, are included in a correct manner. The dynamic wind turbine loads due to the change of rotor speed or blade pitch angle by the controller are also properly modelled. Both aeroelasticity and hydroelasticity are therefore considered, but the effect of the aeroelasticity is much more important than that of the hydroelasticity, since the blades are more flexible than the substructure.

Currently, most of the numerical tools dealing with coupled analysis of offshore fixed wind turbines apply the BEM method for aerodynamic loads, Morison's formula for hydrodynamic loads, and a beam model for structural members. For monopile or tripod offshore wind turbines, coupled analysis tools have been developed as an extension of aerodynamic codes for onshore wind turbines, and have been benchmarked in a code-to-code comparison and reported in the IEA OC3 study (Jonkman *et al.*, 2010).

Jacket support structures are more complicated in geometry. In order to analyze jacket wind turbines, an integration of existing aerodynamic, hydrodynamic, and structural analysis codes is needed. Such numerical tools exist. For example, Seidel *et al.* (2009) compared the coupled tool of FLEX 5-ASAS(NL) with the measurement of the jacket wind turbine in the DOWNVInD demonstration project, and the preliminary comparison showed a good agreement. Another example is the nonlinear aero-elastic code ADCoS-Offshore (Moll *et al.*, 2010).

More coupled analysis tools are now under development and need to be verified through code-to-code or code-to-experiment comparison. As a continuation of the IEA OC3 work, the ongoing IEA OC4 study is now comparing many of the existing analysis tools for a reference jacket wind turbine, developed in the EU FP6 UpWind project.

More details concerning the numerical tools for offshore fixed wind turbines are discussed in Section 2.5.

2.3 Floating Solutions

2.3.1 Fundamental Differences as Compared with Fixed Wind Turbines

Main Characteristics of Floaters vs. Fixed Offshore Structures

All loads on a fixed structure, both vertical and horizontal, must be carried by the structure and transferred down to the foundation at the sea bed. A common feature of

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all types of floaters is that they utilize excess buoyancy to support the payload (tower and nacelle) and the horizontal loads are carried by the station keeping system. Fixed structures are stiff in the horizontal plane with a natural period normally well below 5 *s*, while all floater types naturally have surge, sway, and yaw periods generally longer than 100 *s*, due to the fact that they are "soft" in the horizontal plane. The natural period of a fixed structure is governed by the stiffness of the structure, while the natural period of a floater in surge, sway and yaw is governed by the station-keeping system.

Floater Design

Depending on the area and the sea state, ocean waves contain 1st harmonic wave energy in the period range of 5 – 25 *s*. For a floating unit, the natural periods of motions are key features, and in many ways reflect the design philosophy. As an example, the heave natural period for a spar is normally positioned above 25 *s*, while the natural period for a tension-leg-platform (TLP) is normally below 5 *s*, as indicated in Figure 5.

The fundamental differences among floaters are related to their motions in the vertical plane, i.e. heave, roll, and pitch. Floater motions are important for the choice of power take-off cables, umbilicals and mooring systems. Typical heave transfer functions for different floaters and a storm wave spectrum are shown in Figure 6. The figure is based on DNV RP-F205 (DNV, 2010b).

Floating structures such as spars, semi-submersibles, monohulls, and TLPs are well known by the offshore industry with respect to motion characteristics and critical components. When these structures are used to support wind turbines, new challenges may arise in the design caused by downsizing due to the smaller payload. This applies to the structure, mooring, power take-off cables, and umbilicals. The different floater types have different characteristics, as outlined in the following sub-sections.

Deep Draft Floater Response Characteristics (Spar)

A deep draught floater (DDF) is characterized by small heave motions. An example of a DDF is a spar platform. The main hull of a spar is a vertical cylinder which provides buoyancy. Fixed and floating ballast are often employed at the bottom to control the floating performance. The dominant loads are wind and wave loads. The spar also has a large area exposed to current forces. Low frequency (LF) vortex-induced motions (VIM) may increase the effective drag, leading to higher mean current forces. By adding strakes on the spar hull, possible vortex-induced cross-flow oscillation can be significantly reduced. However, the strakes will increase the mass and the drag forces on the spar. Deep draft floaters' small heave motions are advantageous for the power take off cables, the umbilicals (instrument cables), and the moorings.

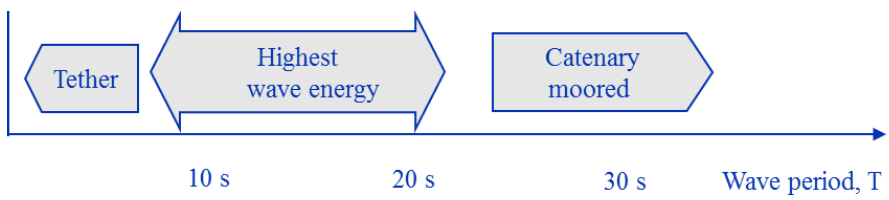

Figure 5: Typical heave periods for different floating solutions vs. location of highest wave

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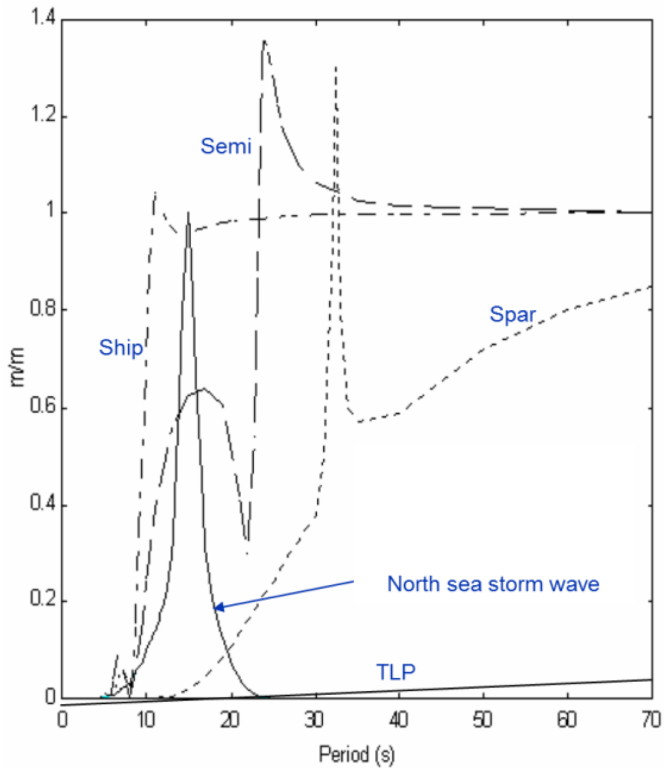

Figure 6: Heave transfer functions for different floaters and storm wave spectrum (DNV, 2010b)

Semi-submersible Response Characteristics

A semi-submersible is usually a column-stabilized unit, which consists of large diameter support columns attached to submerged pontoons. The pontoons may be of different designs, such as ring pontoons, twin pontoons, or multi-footing arrangements. Semi-submersibles have small water-plane areas, which give rather high natural periods in vertical modes. For offshore platforms, the natural period in heave is usually outside the range of wave periods, except for extreme sea states. This implies that a semi-submersible normally has relatively small vertical motions compared to a monohull floater (e.g. barge). However, its behaviour in extreme weather requires flexible, hang off systems or a hybrid arrangement for this concept. A semi-submersible may be equipped with a variety of mooring systems. For wind turbine support structures, heave plates are used to reduce motion (Cermelli *et al.*, 2009).

TLP Response Characteristics

A TLP differs fundamentally from other floater concepts in the sense that it is the tendon stiffness rather than the water-plane stiffness that governs vertical motion. The tension system is a soft spring in surge, sway, and yaw motions, but stiff in heave, roll, and pitch motions. A TLP generally experiences wave frequency (WF) motions in the horizontal plane that are of the same order of magnitude as those of a semi-submersible of comparable size. In the vertical plane, however, the TLP will behave more like a fixed structure, with almost no WF motion response. The tendon stiffness forces directly counteract WF forces.

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Table 1: Typical floaters and boundary conditions

Type	Surge , Sway	Heave	Roll , Pitch	Yaw
Deep Draft Floaters (spar)	C	C	C	C
Semi submersibles	C	C	C	C
Monohull (barge)	C	C	C	C
Tension Leg Platforms (TLP)	C	R	R	C

Higher order sum-frequency wave forces may introduce springing and/or ringing responses in the vertical modes. These effects may give significant contributions to the fatigue responses of the tethers. Set-down is the kinematic coupling between the horizontal surge/sway motions and the vertical heave motions. Set-down is important in the calculation of tether forces and power take-off cable responses.

Monohull Response Characteristics

A monohull structure might be shaped like a barge or a ship. Due to a large waterplane area, these structures are susceptible to large motions, in particular head sea and beam swell. Significant roll accelerations may occur and thus have an impact on the turbine. Such roll accelerations will also have large impact on the design of cables and the mooring system. Large bilge keels may be necessary to control motions. The selection of proper roll damping is important in predicting responses.

2.3.2 Comparison of Different Concepts

The selection of substructures for floating wind turbines depends on several parameters. The main boundary conditions are the environmental conditions (wind, wave, current) and the water depth at the site. These boundary conditions are somewhat correlated, especially with respect to wave heights, as waves will eventually be limited in height, due to finite water depth.

Existing floating offshore structures form the main reference base. However, floating wind turbine structures will be of smaller sizes and volumes even though the drafts may be of the same order of magnitude as the drafts of existing offshore floating structures. For concepts with multiple turbines mounted, the horizontal dimension may be larger in the horizontal plane. The floaters may either be compliant (C), or restrained (R) for the global modes of motions; surge, sway, heave, roll, pitch and yaw. Table 1 shows some typical floater types with a basis in floating offshore structures for easy reference. Restrained modes will not imply a total fixation, but displacements in the order of centimetres will be derived (e.g. an elastic stretch of a TLP tendon) compared to displacement in the order of metres for a compliant mode.

An overview of different floater types is also given in Ronold *et al.* (2010).

2.3.3 Challenges of Floating Wind Turbines

General

The main challenge of floating wind turbines is to reduce the unit costs of the produced energy, while at the same time maintaining an acceptable level of safety. All aspects contributing to the cost should be improved, such as:

- Development of design rules;
- Development and validation of design tools;
- Turbine design;
- Design of station-keeping;
- Design of power take-off cables and umbilicals;

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- Design of foundations for cyclic loads;
- Determination of accidental load events;
- Requirements for floating stability and minimum compartmentalization;
- Fabrication, transportation, assembly, and installation costs;
- Corrosion engineering and control; and,
- Cost optimized operation, including maintenance and repair.

Combined Wind and Wave Loading / Wind Turbine Control

New floating wind turbine concepts must ensure that peculiar effects like Mathieu Instability (MI) and vortex-induced motions (VIM) for a DDF are unlikely to occur or can be controllable. For example, care must be taken in selecting eigenperiods in heave, roll, and pitch for a DDF. Concepts with abrupt changes in waterplane stiffness and metacentric height will also have focus on MI. Model testing will be the ultimate method for this, but state-of-the-art offshore design practices and methodologies provide sufficient guidance for early design stages. Reference is made to Ronold *et al.* (2010).

According to Roddier *et al.* (2009), the aero-hydro coupling of the wind turbine with the floater needs to be investigated in detail. Software must be validated against model and full-scale tests. A significant amount of work on the qualification of the turbine is needed. The turbine itself will most likely need to be improved and strengthened. Optimum floater design must be achieved in order to create a cost-effective solution for offshore floating wind turbines.

Berthelsen and Fylling (2011) present a design optimization approach which combines available response analysis programs for mooring system forces and vessel motions with a gradient search method for the solution of nonlinear optimization problems with arbitrary constraints. They considered the following design constraints: vessel motion, tower inclination, tower top acceleration, spar draft, mooring line load limitations, minimum horizontal pretension, and maximum horizontal offset.

Fatigue

Fatigue of a floating structure will be a larger challenge than for a fixed. Reference is made to Aubault *et al.* (2009), who state that the wind force is essential to the strength behaviour of the WindFloat, since its contribution to the bending stress of the structural members is significant. The effect of aerodynamics must be included in the detailed structural analyses.

Karimirad and Moan (2010) compare the structural response of the floating wind turbine in both survival and operational conditions, to show the importance of analysing the structural response in survival conditions to obtain lifetime optimization.

Station-Keeping

Optimizations of station-keeping systems may lead to non-redundant systems where a mooring failure may lead to a loss of position and possible conflict with adjacent wind turbines. If some of the structures in a wind park are planned to be manned during storms (e.g. substations), this might also influence the design requirements. Progressive drifting of floating units should be considered carefully. Reference is made to Suzuki *et al.* (2009a).

Floating Stability

For manned structures, existing offshore codes can be applied for stability check under both intact and damaged conditions. For unmanned structures, other and more

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relaxed rules might be appropriate. For unmanned structures, additional compartmentalization is usually not required, unless more stringent requirements (governmental, operator) have been put forward. The need for a collision ring in the splash zone will have to be evaluated with basis in local legislation/requirements, manned/unmanned status, substructure material (concrete/steel/composites), size of service vessels in the area, and resistance to boat impacts.

Power Take-off Cables and Umbilicals

The design of cables for the transfer of electricity and other signals should be integrated with the design of the floater and global performance. Typical issues include the selection of the hang-off location, the motions at hang-off and relevant configuration (e.g. pliant wave, lazy wave, steep wave, or other). The design of umbilicals/cables should follow the same ISO codes as those used for the design of traditional offshore applications. Emphasis should also be placed on the cable installation phase, in order to ensure that the system is positioned as planned. Strakes and/or fairings may be needed to limit vortex-induced vibrations (VIV), or vortex-induced motions (VIM). VIV would typically involve the bending of long slender members either due to wind or to wave/current for the submerged members. VIM typically involves rigid-body motions (in-line, or cross flow) of the complete substructure, causing direct impact on mooring and tethers, as well as cables. Model testing is needed to check the susceptibility to VIM. Alternatively, computational fluid dynamics (CFD) testing is sufficient if the CFD software has been validated.

2.3.4 Coupled Dynamic Analysis of Floating Wind Turbines

For design purposes, dynamic responses of floating wind turbines in wind and waves need to be determined, which includes those of the rotor blades, tower, floater, and mooring system. Since a floating wind turbine has many natural modes of motions or vibrations with different periods that might be excited by the individual wind and wave loads or combined loads, it is important to obtain the dynamic responses considering the wind and wave loads simultaneously. Time-domain analysis is preferred due to the nonlinear aerodynamic loads and control action.

Numerical tools have been developed or are under development, to analyze the dynamic responses for various floating wind turbine concepts. The IEA OC3 study compared various numerical codes for a 5 MW spar floating wind turbine (Jonkman and Musial, 2010), while the comparison of a semi-submersible concept is now being carried out in the OC4 study. Typically, the BEM method with engineering corrections is used for aerodynamics, while the hydrodynamic loads are based on Morison's formula or potential theory.

The spar-supported floating wind turbine is the only concept that has been extensively analyzed. For analysis of the HYWIND concept, the integrated SIMO/RIFLEX/HAWC2 simulation tool has been developed and has shown a good agreement on dynamic responses with the model test results and the prototype test results (Skaare *et al.*, 2007, Hanson *et al.*, 2011). HAWC2 has also been applied to analyze a spar floating wind turbine, for example by Karimirad and Moan (2010), where the hydrodynamic loads on the spar are based on Morison's formula and the mooring system is modelled as nonlinear springs.

Jonkman (2007) has developed a fully coupled time-domain aero-hydro-servo-elastic simulation tool, FAST, with AeroDyn and HydroDyn, where the hydrodynamic loads obtained from WAMIT (Lee and Newman, 2006) are used. This tool has been used

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for the dynamic analysis of three floating wind turbine concepts, supported by spar, TLP, and barge, respectively (Jonkman and Matha, 2011). The studies found that the platform motion-induced ultimate and fatigue loads for all turbine components in the barge concept are the highest among the three concepts, while the difference between the spar and the TLP concepts is not significant. Moreover, as compared with the onshore wind turbine, the dynamic responses of the blades in the spar and TLP concepts are not very different, while those of the tower base are 60 % and 30 % larger for the ultimate loads for the spar and the TLP concepts, respectively.

For a floating platform with a pitch-regulated turbine, the conventional land-based controller may give a 'negative damping' effect and induce large resonant pitch motions of the platform. This is because, for the wind speed larger than the rated wind speed, the blade-pitch controller is activated to obtain constant power output. However, when the relative wind speed increases due to the pitch motion of the platform, the wind thrust force decreases, leading to a 'negative damping' effect. The effect can be avoided by tuning the controller (Larsen and Hanson, 2007, Skaare *et al.*, 2010) or adding a tower-feedback control loop (Jonkman, 2007).

More details concerning the numerical tools for offshore floating wind turbines are discussed in Section 2.5.

2.4 Design Rules for Fixed and Floating Wind Turbines

Current standards for design of offshore wind turbines and their support structures essentially consist of the following four documents:

- IEC61400-3
- DNV-OS-J101
- GL (IV Part 2)
- ABS #176

The IEC standard 61400-3 (IEC, 2009) was issued in 2009, close to ten years after the decision was made to develop this standard. The DNV and GL standards, DNV-OS-J101 (DNV, 2011) and GL (IV Part 2) (GL, 2005), were first issued in 2004 and 2005, respectively. These two industry standards – mostly synchronized with IEC61400-3 – form the design standards which are used as a basis for the project certification services that DNV and GL offer for offshore wind farm projects. The ABS standard #176 (ABS, 2010) was first issued in 2010 and is also mostly aligned with IEC61400-3; however, it is the only standard among the four to address wind turbines in areas prone to tropical storms.

2.4.1 Status Regarding Design Standards for Floating Wind Turbines

The four standards available for the design of offshore wind turbines and their support structures are all encumbered with the common limitation that, in practice, they are restricted to the design of bottom-fixed structures only, as they do not cover floater-specific design issues, such as stability and station keeping. The IEC standard does not contain specific requirements for floaters. The DNV and GL standards do not explicitly exclude floating wind turbine solutions; however, they do not deal with floater-specific issues. For floater-specific issues, such as mooring, the GL standard references other GL rules, which are not dedicated to wind turbines and thus not calibrated for wind turbine loads. The ABS standard specifically excludes floating wind turbine installations.

The following subsections summarize the status for various stakeholders and publishers of standards, such as regulatory bodies and certifying bodies, with respect to standards for floating wind turbines and their support structures.

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DNV

DNV has developed a 'Guideline for Offshore Floating Wind Turbine Structures', which was issued in 2009 as a technical report to supplement the existing DNV standard for bottom-fixed support structures, DNV-OS-J101. This guideline, less formal than an official standard document, addresses floater-specific issues, such as stability and station-keeping. It references DNV (2009) and Ronold *et al.* (2010, 2011). In 2011, DNV initiated a joint industry project with the aim of developing a new standard for the design of floating support structures for wind turbines.

GL

Extension of the current GL standard to further floater-specific requirements is under development, focusing on stability requirements and mooring applications.

BV

BV has developed a guidance note for the 'Classification and Certification of Floating Offshore Wind Turbines'. The guidance note, NI572, was issued in 2010 and appears to be produced by BV's Marine Division, to allow for classification of floating support structures. The document references BV (2010). BV appears not to have any design standard of their own for offshore wind turbines and their support structures.

IEC

A Korean proposal, submitted in 2010, for development of an authoritative standard for floating offshore wind turbines was considered premature by the TC88 committee and was therefore changed by the committee into a proposal for development of a technical IEC specification. This proposal has been accepted by a majority of the voting TC88 committee members and an IEC working group has been formed and has begun the task of developing the technical specification. In addition, DNV has proposed an extension of IEC61400-3 for floating wind turbines (DNV, 2010a). Much of this proposed extension is based on the DNV guideline, DNV (2009).

2.4.2 Discussion

Current standards for the design of bottom-fixed wind turbine structures reflect that it is cost optimal to carry out site-specific designs, for example resulting in individual pile lengths for the monopiles in a large wind farm of turbines supported by monopiles. The individual pile lengths match different water depths and different soil properties between wind turbine positions. Structural steel is also expensive.

New standards for floating wind turbines will be likely to be different, in that it will be cost efficient to use identical mass-produced units for all supporting floaters on a large wind farm. This means that structural design will be likely to be optimised for a fleet of floaters for site-specific environmental data rather than optimised for each individual support structure, as is usual for fixed support structures. In particular, in light of such a mass-production approach to support structures for floating wind farms, it becomes very important for new design standards to ensure sufficient safety against systematic errors in design.

Keeping cost low is important for the design of both fixed and floating wind turbine structures, since the wind farms on which they are used are often economically marginal projects. When new design standards are developed, it will therefore be a challenge to establish more accurately the safety level necessary for the wind turbines and their support structures on a wind farm. The consequence of failure of a single wind turbine will likely be smaller on a large wind farm than on a small wind farm.

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Therefore, the required target reliability for the design of a wind turbine and its support structure would depend on the number of turbines on the wind farm. This issue of target safety level applies to both fixed and floating support structures.

For floating wind turbine structures, in contrast with bottom-fixed structures, low frequency response is an issue. This necessitates models to adequately capture environmental conditions in the low frequency range, beyond what is included in current standards for bottom-fixed turbines. This needs to include, but is not limited to:

- Adequate representation of wind in the low frequency range, where some of the commonly applied power spectral density models for wind are known to not provide a particularly good representation;
- Definition of gust events based on gust periods in excess of 12 seconds. The definition must cover expected events and reflect frequencies encountered for the dynamics of floaters;
- An alternative two-peaked spectral density model for floaters, which can be excited by swell. The uni-modal JONSWAP wave spectrum, which is commonly used for representation of wave energy; is insufficient, and
- Set-down effects for water level. Water level may be of significant importance for tension leg platforms.

The low frequency response of floating support structures means that they require longer simulation periods than those usually needed for bottom-fixed structures. A simulation period of load and response of 3 to 6 hours may be required to accurately capture nonlinearities, second-order effects, and slowly varying responses. This poses some challenges, as wind cannot be considered stationary over time scales as long as 3 to 6 hours (Ronold *et al.*, 2010).

2.5 Numerical Tools for Dynamic Analysis of Offshore Wind Turbines

This section describes the current development of numerical tools for analysing offshore wind turbines. There are two types of analysis of the dynamics of wind turbines-frequency domain and time domain. Frequency domain analysis has been used in the oil and gas industry, and is simple to use. However, it cannot take into account nonlinear dynamic characteristics and the response due to control systems, which are important in wind turbine system analysis. Time domain analysis is widely used for the design and analysis of wind turbine systems.

The IEA Wind Task 23 Subtask 2 project (Offshore Codes Comparison Collaboration, or OC3), compares the results of a dynamic analysis of fixed bottom wind turbines with various codes (Jonkman and Musial, 2010). The codes used are FAST, FLEX5, Bladed, Bladed Multibody, ADAMS, SIMPACK, HAWC, HAWC2, BHawC, and ADCoS-Offshore. A list of the participation codes and their capability is shown in Table 2. The codes were applied to monopole supports with rigid foundations, monopole supports with flexible foundations, and tripods. Various response parameters were selected for comparison, considering a number of defined load cases, including constant and uniform wind speeds and stochastic wind field, and regular and random waves. The main conclusion from this benchmark work is that these codes agree well in general for both the monopile and tripod wind turbine models. However, the differences in the response parameters between the codes are also observed, which are mainly due to the differences in the structural modelling, the wind field modelling, the implementation of the BEM code, and the discretization of substructure for hydrodynamic loading.

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Table 2: Overview of the codes participated in the IEA OC3 benchmark study

FAST	FLEX5	Bladed	Bladed Multibody	ADAMS	SIMPACK	HAWC	HAWC2	BHawC	ADCoS-Offshore
Code Developer									
NREL	DTU	GH	GH	MSC + NREL	SIMPACK + SWE + NREL	Risø	Risø	Risø + Siemens	ADC + IWES
OC3 Participant									
NREL + CENER	DONG + SWE + Vestas	CENER + GH	GH	NREL	SWE	DNV + Risø	Risø	Siemens	IWES
Aerodynamics									
(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS	(BEM or GDW) + DS
Hydrodynamics									
($Airy^+$ or UD) + ME	($Airy^+$ or UD or Stream) + ME	($Airy^+$ or Stream) + ME	($Airy^+$ or Stream) + ME	($Airy^+$ or UD) + ME	None	($Airy^+$ or UD) + ME	($Airy^+$ or UD) + ME	($Airy^+$ or UD) + ME	($Airy^+$ or UD) + ME
Control System (servo)									
DLL, UD, SM	DLL, UD	DLL	DLL	DLL, UD	DLL, UD	DLL, UD	DLL, UD, SM	DLL, UD	DLL, UD
Structural Dynamics (Elastic)									
FEM^P + (Modal / MBS)	FEM^P + (Modal / MBS)	FEM^P + (Modal / MBS)	MBS	MBS	MBS	FEM	MBS / FEM	MBS / FEM	FEM

ADC – Aero Dynamik Consult Ingenieurgesellschaft mbH
$Airy^+$ – Airy wave theory; (+) with free surface connections
BEM – blade-element/momentum
DLL – external dynamic link library
DS – dynamic stall
GDW – generalized dynamic wake
FEM^P – finite-element method; (P) for mode preprocessing only
MBS – mulibody-dynamics formulation
ME – Morison's equation
MSC – MSC Software Corporation
SM – interface to Simulink® with MATLAB®
UD – implementation through user-defined subroutine available

The project is continuing in the IEA Wind Task 30 project (Offshore Codes Comparison Collaboration Continuation, OC4). This project will compare the results of jacket substructures (IEA Wind Task 30 Website, 2011).

As for the dynamic analysis of floating wind turbines, aerodynamics, hydrodynamics, control commands, and structural dynamics should be solved simultaneously, i.e. a coupled analysis of aero-hydro-servo-elastic. Cordle and Jonkman (2011) give a good summary of programs for the coupled dynamic analysis of floating wind turbines. The OC3 study has compared various codes for a spar floating wind turbine. The OC4 study will examine a semi-submersible floating wind turbine.

Among these numerical codes, one of the best known analysis tools is FAST, developed by the National Renewable Energy Laboratory (NREL) (Jonkman and Buhl, 2005). It was developed for fixed wind turbines, but it was extended to enable coupled dynamic analysis of floating wind turbines. It covers the structural dynamics, aerodynamics (AreoDyn), hydrodynamics (HydroDyn) and quasi-static mooring analysis. For structural dynamics, it uses modal and multi-body system dynamics (MBS) representation. For MBS, it has the option of using the ADAMS commercial program. The hydrodynamic forces include hydrostatic force, nonlinear viscous drag from Morison's equation, wave exciting forces, and radiation force. The hydrodynamic coefficients are calculated using WAMIT (Lee and Newman, 2006).

A few programs are combined with FAST to take advantage of the program openness. One of them is the CHARM3D-FAST combination. CHARM3D is a time domain floater and mooring line analysis tool developed by Shim and Kim (Shim and Kim, 2008, Bae *et al.*, 2011). CHARM3D also uses WAMIT to calculate the hydrodynamic coefficients and mean drift forces of floaters. TimeFloat, a time-domain software tool for analyzing floating structures, is also combined with FAST for a coupled dynamic analysis of floating wind turbines (Cermelli *et al.*, 2009, Roddier *et al.*, 2010). SIMPACK, a commercial MBS code, also uses AeroDyn and HydroDyn to simulate floating wind turbines (Matha *et al.*, 2011).

HAWC2 was developed at Risø DTU (Larsen, 2009). It was originally intended for

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calculating onshore wind turbine response in time domain and has a structural formulation based on multi-body dynamics. It has been extended for dynamic analysis of both offshore fixed and floating wind turbines. The hydrodynamics is based on Morison's equation.

WindHydro is a coupled dynamic analysis program for floating wind turbines developed by Rim *et al.* (2010, 2011). It uses AeroDyn of NREL to calculate the aerodynamic forces and their own code to calculate the hydrodynamic coefficients and forces. DAFUL, a commercial multi-body and structure dynamics analysis program, is used for multi-body dynamics analysis considering the flexibility of the blades and the tower.

SIMO/RIFLEX is a time domain offshore simulation code and was extended to analyse wind turbines. Two means of calculating aerodynamic forces exist. One uses its own aerodynamic module (Fylling *et al.*, 2009) and the other uses HAWC2, which is for the dynamic analysis of fixed wind turbines (Skaare *et al.*, 2007).

There are two commercial codes for the dynamic analysis of wind turbines – GH Bladed and S4WT. GH Bladed, developed by GL Garrad Hassan, was developed for onshore fixed wind turbine dynamic analysis and has been extended to analyze offshore wind turbines by including hydrodynamic loads (GL Garrad Hassan, 2010, Henderson *et al.*, 2010). Flexible structural parts, such as the blades and the towers, are modelled by modal representation. The structural dynamics part was rewritten to incorporate MBS from FEM based code. Morrison's equation is used to calculate the hydrodynamic forces.

S4WT, developed by SAMREC, was also developed for onshore wind turbines and extended to analyse offshore wind turbines, both bottom fixed and floating. With this method, jacket and monopile modelling can be done in parametric modelling and floating turbines can be completed via user defined modelling (Heege *et al.*, 2010, 2011). Aerodynamic and hydrodynamic coupling analysis is also possible. Analysis can be done according to GL guideline and IEC codes.

3 WAVE ENERGY CONVERSION

Wave energy, like wind, suffers from the variability of environmental conditions, which may range from flat calm to severe waves. With small waves during a given period, limited energy can be produced. On the other hand, extreme waves may also limit the ability of the structure to capture energy and may even cause damage to the structure. The structure must be designed to the average wave conditions to be efficient and economical, but must also withstand the more severe conditions and possibly continue to operate. Although wave energy is much more plentiful than wind, exploitation of wave energy has lagged behind that of wind (Falcao, 2010). This is probably due to the steady progression of wind energy exploitation from land-based to near-shore locations and further out to sea. There are a wide variety of wave energy exploitation concepts, and more than 150 concepts can be listed to date in the following categories:

- Attenuator;
- Point absorber;
- Oscillating Wave Surge Converter;
- Oscillating water column;
- Overtopping/Terminator device;
- Submerged pressure differential;
- Other emerging technologies.

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Until 2009, most of the concepts were still at an early stage of development, but the last few years have seen a considerable increase in the construction of reduced and full-scale demonstrators which may indicate a new trend that wave power could now become attractive commercially to developers and investors.

3.1 Review of Latest Developments

3.1.1 Full-scale Prototype Installations

The European Marine Energy Centre (EMEC) has seen a considerable increase in activity as a test site since 2009 for tidal energy converters, and a growing number of wave projects are planned for commissioning in the near future.

Aquamarine Power Ltd launched their nearshore "Oyster" device in 2009. Oyster 1 demonstrated the feasibility of using wave energy to pump high pressure water to an onshore hydro-electric turbine to generate electricity. The machine was removed in spring 2011 for analysis. A second Oyster wave energy device is due for commissioning, which will be followed by two further Oyster devices in 2012 and 2013, as part of a small array. Each Oyster 2 machine will have a generating capacity of 800 kW and will measure 26 m wide by 16 m high.

E.ON have deployed the first Pelamis P2 device. The second generation device, built by Pelamis Wave Power, arrived in Orkney in July 2010 and is undertaking a planned work-up programme of testing.

Finnish company Wello Oy will deploy their Penguin device in 2012. The Penguin is designed to capture rotational energy generated by the movement of its asymmetrically shaped hull. Constructed in Riga, Latvia, the device arrived in Orkney in June 2011. Approximately 30 m in length, the 1600 t device is expected to produce between 0.5 – 1 MW of power.

The Seatricity concept involves multiple floats travelling up and down with the waves, operating pumps to pressurize sea water, which is piped ashore to drive a standard hydroelectric turbine to produce electricity. The device is planned for deployment in 2012. Another development to take place in early 2012 in Portugal is the final testing and assembly of AW-Energy's first 3 × 100 kW WaveRoller power plant. The deployment is scheduled to take place in the waters off Peniche as soon as weather conditions permit.

Scotland-based AWS Energy has undertaken scale model testing in controlled tank conditions and to prove the manufacture, installation, maintenance, and durability of the flexible wave energy absorber membrane. A typical device will comprise an array of 12 cells, each measuring around 16 m wide by 8 m deep, arranged around a circular structure with overall diameter of 60 m. Such a device is capable of producing an average of 2.5 MW from a rough sea whilst having a structural steel weight of less than 1300 ts. The AWS-III will be slack moored in water depths of around 100 m using standard mooring spreads. A single-cell test apparatus is planned for deployment in UK waters during 2012.

The 150 kW PowerBuoy PB150 from Ocean Power technologies (OPT) was deployed at sea in 2011 for a series of test at a site approximately 33 nautical miles from Invergordon, off Scotland's northeast coast.

Port Kembla in Australia was the site of Oceanlinx Mk3 Pre-Commercial. The unit was deployed for three months, from February to May, 2010, and operated successfully during that time as one of the world's first grid-connected generators of electricity from

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ocean waves. The device unfortunately broke free from its mooring in a storm and crashed into the breakwater and eventually sank.

There are many other studies reported e.g. Estefen *et al.* (2010) at different stages of development providing useful insights into structural and control challenges associated with this form of energy capture.

3.2 Current Research Activities

3.2.1 Numerical Predictions

Wave energy devices are varied but can be broadly classified into solid body, air-chamber, and overtopping devices. These types of devices lend themselves to analysis by well-established potential flow methods. Although simplified methods have been utilized with some success in parametric design studies, the most common analysis methods involve the use of floating free-surface body panel methods which are used extensively in ship and floating offshore platform design and analysis (Falnes, 2002). These numerical methods are implemented in a number of commercial computer programs and it is generally possible to incorporate air chambers into the analysis. Linear problems can be solved in the so-called frequency domain, but as nonlinearities and complex control strategies become important, time domain methods may have to be utilized. Frequency domain methods are relatively inexpensive to implement but have limitations. Time domain methods are more capable of taking into account non-linearities and complex control strategies, but are more difficult to understand and time-consuming to implement. Significant research effort continues concerning wave prediction and the manner in which waves interact with tidal flow and sediment transportation (Previsic *et al.*, 2004, Warner *et al.*, 2010, Siddons *et al.*, 2009, Brown, 2010).

Numerical modelling of ships and floating offshore platforms has been affected by the advances in hardware and software computational capability. This has been particularly true with regards to the utilization of computational fluid dynamics (CFD) tools for hydrodynamic design. Although CFD has experienced tremendous development over the last several years it still has limitations with regards to analysing free surface problems.

3.2.2 Experimental/Concept Demonstration

Experimental verification of concepts is an important step before concepts are demonstrated on-site or at full scale, but model testing of wave energy devices suffers from the same limitations which floating body model tests do with the additional complications of scaling issues associated with the air chamber, and also power take-off and control mechanisms. It is critical to utilize large scale models in order to minimize the so-called "scale effects". However, large-scale models are expensive to build and test and a limited number of facilities exist to test at very large scale. In order to eliminate scale effects and convincingly demonstrate a concept, full-scale demonstration is the eventual goal. However, full-scale demonstration is expensive and it may be difficult or impossible to measure or control the environment in order to convincingly demonstrate a concept.

3.2.3 Mooring Systems

Although not all devices are floating, fixed mooring is an important aspect for the floating devices. The mooring concepts utilized for wave energy devices are similar to those utilized in floating platforms. The mooring systems can generally be classified

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into slack catenaries and taut moorings. However, in order to fully realize the potential of various concepts, the requirements of mooring systems may in some cases be more demanding than ships and floating offshore platforms. Moreover, if closely-spaced arrays of devices are considered, the interference of the mooring may result in a complex mooring arrangement (Falcao, 2010).

3.3 Power Electronics, Control

Power electronics for controlling devices and taking power are ultimately the most critical component. However, control and power electronics cannot be considered in isolation, but must be part of the overall system design. Moreover, the control and power take-off electronics must also consider an accurate physical model of the device in order to be fully effective. The issues associated with control and power take-off are similar to those which wind turbines experience, but are even more challenging due to the complex hydrodynamic interactions associated with random waves. The most significant issue is the fact that real sea waves are random. It is important to understand the amplitude and frequency variation of the sea waves. Optimal performance of wave energy devices occurs at resonance – i.e., when the device natural frequency and the excitation frequency are equal. Since the excitation frequency is constantly changing, some sort of active control mechanism is required in order to optimally capture the available wave energy.

4 TIDAL AND OCEAN CURRENTS ENERGY CONVERSION

This chapter presents an update of the previous reports of the ISSC specialist committee V.4, "Ocean, Wind and Wave Energy Utilization", focusing upon different aspects of tidal energy conversion, with the addition of a section on ocean current energy conversion. Since 2009, many concepts have progressed to the stage of demonstrators being built and tested at model and at full-scale, which provide a valuable feedback in terms of structural reliability and a vast amount of in-situ experimental data for the design teams to review their initial design parameters. However, developers and suppliers, particularly in the area of electricity generation and power control systems, are still reluctant to make site data available to the wider research community, which does not favour the progress of research in this critical area of power control.

4.1 Tidal Currents Energy Conversion

4.1.1 Technologies

The 2006 and 2009 reports extensively covered the different concepts available at the time. Briefly, the mechanisms for tidal energy generation can be classified to date into four main categories, with the possible inclusion of an additional new technology based on vortex-shedding past cylinders:

- Horizontal axis tidal turbine (HATT);
- Vertical axis tidal turbine (VATT) ;
- Oscillating tidal hydrofoil (OTH); and
- Vortex-induced vibrating tidal cylinders (VIVTT).

HATT and VATT can be found in "open" or "ducted" configurations. Ducted configurations seem to be considered as they can present functional advantages, especially for maintenance, but also for the increased performance they seem to offer.

Depending on the depth of deployment of the converter, the structural foundation can follow one of the following types:

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- Piled on the seabed with converter at a set depth;
- Piled on the seabed with converter at a variable depth (surface piercing);
- Moored from a floating structure;
- Guyed tower;
- Telescopic;
- Tethered; and
- Seabed standing under gravity.

4.1.2 Review of Latest Developments

Although tidal barrages are not the main consideration here, a brief mention should be made about the Severn Estuary project (UK). After the project of a tidal barrage was abandoned by the British government, an alternative project, the "Severn Tidal Fence Consortium" was set up to undertake a feasibility study to assess the potential for a large tidal fence system spanning the width of the Severn Estuary. The fence system would consist of a string of tidal stream energy converters spanning the estuary, with a free passage navigation gap. This new concept is claiming to have appreciable benefits when compared with tidal barrages, including reduced environmental impact, less disruption to shipping, and lower capital investment (Giles, 2010).

If vertical axis machines are mostly considered, it is interesting to note the deployment in 2009 of the 100 kW hydrofoil demonstrator, "Pulse-Stream 100", by Pulse Tidal Ltd, in the River Humber in the UK, which is a shallow water site of $9\,m$ depth. A $1.2\,MW$ prototype is planned for commissioning in 2012 in the Isle of Skye Waters.

Among the latest developments, it is worth noting the "Tidal Flyer," which is a novel, patented concept for extracting the kinetic energy from tidal currents developed by Open Ocean Energy Ltd in collaboration with HMRC of University College Cork. The fundamental concept of the device uses self-trimming tails in order to control the foils moving under water. The design ensures that the tail is always aligned to the apparent flow of the water and therefore keeps the main foils at the same angle of attack to the apparent flow and thereby creates maximum force within the cables. The system has been tested at model scale in the ocean engineering institute IFREMER. In a full system, the self-trimming tail oscillates from side-to-side to control the angle of attack of the main foils in each array. The resulting force in the cables is transferred to vertical shafts via the pulleys, which then feeds into the power take-off (PTO) system. This system has the advantage of operating at low current velocities of the order of $2\,kn$ ($1\,m/s$), which will have significant advantages in regard to the available sites for development and in the maintenance of the system.

A new technology based on the forces induced by a cylinder subject to vortex shedding is the VIVACE Converter developed by the University of Michigan under Vortex Hydro Energy LLC. This concept, which was, so far, at a laboratory scale experimental stage, is now being developed further as a demonstrator in the Detroit River.

Another similar concept is being developed in the University of Georgia (USA), which is a novel low-energy vortex shedding vertical axis turbine (VOSTURB). The rationale for this concept is to circumvent the inefficiencies and challenges of hydro-turbines in low velocity free tidal streams. VOSTURB aims to capture the energy of the vortices by installing a hydrofoil subsequent to a bluff body. This foil, free to oscillate, translates the vortex energy into oscillatory motion, which can be converted into a form of potential energy.

There continues to be fundamental concept development e.g. Bruder *et al.* (2011),

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however the majority of research and development is now focusing on engineering optimization of components and devices e.g. Davies *et al.* (2011).

4.1.3 Full-scale Prototype Installations

Over the last few years, there has been a very significant increase of full-scale prototypes being commissioned. The UK has been particularly active, mostly at the European Marine Energy Centre (EMEC) based in the Orkney Islands. Installed as part of the Deep-Gen III project, co-funded by the UK government-backed Technology Strategy Board, the Rolls-Royce prototype tidal turbine was deployed in 2010 at the EMEC offshore test site off the Orkney Islands, Scotland. It is the first EMEC located project to both receive Renewable Obligation Certificates and to reach 100 MWh of supply to the grid.

The Atlantis Resources Corporation successfully re-deployed its AK-1000 tidal turbine on its subsea berth in the summer 2011, after initial trials in August 2010. This turbine has an $18\,m$ rotor diameter, weights $1300\,t$, and stands at a height of $22.5\,m$. Voith Hydro and RWE Innogy commenced preparatory works in the summer of 2011 by installing the monopile for their $1\,MW$ tidal turbine, which will be developed in 2012 through the joint venture company Voith Hydro Ocean Current Technologies.

Scotrenewables deployed its SR250 in March 2011 and reached the stage of power generation in September 2011. The testing programme involved towing the device to simulate tidal flow in a controlled manner before deploying the device in the Falls of Warness. DeltaStream, which is a gravity-based standing device developed by Tidal Energy Ltd, based in Wales, has a planned installation in 2012 in Ramsey Sound off the Pembrokeshire coast. Hammerfest Strom UK Ltd is planning to install the HS1000 tidal turbine at EMEC in 2012.

Outside the UK, the emergence of full-scale installations was enhanced in recent years by the support of several industry leaders across borders. For instance the Irish company, Open Hydro, partnered the French utility company EDF, and DCNS, the navy shipbuilder. The first $2\,MW$ OpenHydro unit was towed from Brest on 31 August 2011 for deployment in $35\,m$ of water on the seabed off the island of Brehat in Brittany.

4.1.4 Current Research Activities

General ocean engineering and coastal engineering developments are certainly useful in marine renewable energy in general, and particularly in tidal energy, but current methods still present some shortfalls, due to the specific design challenges of tidal energy converters.

Environment Modelling

Prediction tools for tidal and ocean currents modelling are available. In the case of tidal currents public entities, universities and private companies developed methods of prediction for a wide range of sea users (merchant service, fishing, and coastal management). These predictable data are of first interest for tidal energy. If the prediction of surface current is widely available, the prediction of the current profile at a given location is still very much in its infancy, and is, in fact, very complex, due to the fact that tidal currents are very much site-dependent (Lorke and Wüest, 2005, Liang *et al.*, 2008, Liang *et al.*, 2007). Such information, though, is critical to predict not only the power output but also the load cases, in terms of structural design. Data acquisition campaigns using Acoustic Doppler Current Profilers (ADCP) seem to be the only method currently available to collect large data sets, space- and time-wise, at

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a given location. Such campaigns are, in practice, technically difficult in strong tidal spots, and costly to implement due to the multiple expectations from such data. If the basic knowledge of the current profile over few tide cycles can be sufficient for a device power prediction, the access to high resolution data sets becomes necessary for the analysis of turbulence levels at a given site.

Waves and Current Interaction

Three general approaches are considered to study the waves and current interaction:

- Semi-analytical methods based on Stokes development, Stream function, and Boussinesq in two dimensions;
- Numerical modelling of waves and current interaction in the spectral domain based on mitigation of waves modelling software (for instance, SWAN, TOMAWAC from EDF, WAVEWATCH from SHOM) and tidal software (for instance, MARS3D from Previmer). The results are spectral parameters of sea states and mean currents. The interaction with tidal devices are simplified;
- Numerical modelling of three-dimensional flow. Turbulence can be calculated based on basic approach by Navier Stokes, where turbulence can be calculated. In a simpler manner, Boussinesq (Bingham, 2009), or other methods based on wave dispersion (Belibassakis, 2011a). These methods are more able to take into account the detailed interaction with the tidal devices. The results are, at first, time domain parameters. Important studies in this area include Pinon *et al.* (2011), Rusu and Guedes Soares (2011), Mycek *et al.* (2011) and Maganga *et al.* (2010a,b).

Effects of Bathymetry

Smooth bathymetry effects can be taken into account by the different approaches presented above. Bathymetry effects are less accessible to semi-analytical methods. Some developments using diffraction and radiation context aimed to cope with sea bottom variation and the waves and current interaction (Belibassakis, 2011b).

4.1.5 Model Testing

In addition to prediction tools, model testing is an essential part in the selection of a turbine for a tidal energy converter, both to gain confidence in the performance and loads developed by the turbine. Most test campaigns focus on two main aspects: turbine performance, hydrodynamic loading, and dynamic behaviour of the overall device during deployment; and, in operation, when the scaling laws can be respected both for the turbine and the structure. An essential advantage of model testing is the access to data at a given angle of incidence where numerical models struggle to converge. There are inherent problems with model testing related to scale effects and the difficulty to reach the desired Reynolds number. The blockage effect (dimensions of model compared to tank section) must be considered with great care. One of the key aspects in selecting a test facility is the decision to use a water circulation channel or a towing tank. The main difference is the absence of turbulence in a towing tank, which can be of interest for some benchmark cases but in reality not pertinent as tidal flows can exhibit large levels of turbulence, which can be replicated in water circulation channels through the usage of variable size nets or honeycomb type devices. Generation of turbulence or sheared flow is easier in a flume tank and can be more realistic in many situations, such as development of the bottom boundary layer or free surface boundary layer, downstream effects of bathymetry, or downstream effects of other turbine wakes. Towing in waves and waves over current are not strictly equivalent,

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depending on the Froude and Strouhal numbers. The kinematics of the flow on the turbine blades may be quite different. Wake measurements can be achieved through the usage of laser-based techniques, such as Laser Doppler Velocimetry (LDV) and Particle Imaging Velocimetry (PIV). LDV collects data in a punctual fashion, while PIV allows collection of slices of information in 2D, which greatly decreases the time required to assess the wake developed by a single turbine, and also when dealing with interaction effects, in the case of turbines in close arrays. The cost of PIV equipment is, however, restricted to a few research bodies with large public subsidies.

4.1.6 Deployment and Installation of Large/Full-scale Devices

Similar operations are routinely carried out in the offshore oil industry when installing sub-sea equipment. There is an existing fleet of vessels that could cater for the specific needs of the tidal energy industry, within certain limits. The technical capabilities of these vessels are very often far beyond what is required for the deployment of a tidal device, but also seem outside the range of budget available in the tidal industry. The most cost-effective concept seems to be the one of a barge towed by one or more tugs and service crafts. STX France Solutions, for instance, built a dedicated barge for the installation of the first $2\,MW$ OpenHydro unit in 2011.

4.2 Ocean Current Energy Conversion

4.2.1 Resources

Ocean currents are strong, uni-directional surface currents located on the western boundary of the world's oceans. Ocean currents, especially the Gulf Stream and the Kuroshio Current, have been the topic of discussion over several decades as an energy resource. However, only one experimental ocean current turbine (OCT) has ever been deployed in the world. The experimental turbine was installed more than two decades ago in Florida current that is a portion of the Gulf Stream, off the coast of southeast Florida (Van Zwieten, 2011).

Global Circulation Models often fail to reproduce the structure of the current that is locally modified by topographic effect and by local winds. Re-analysis has to be adjusted to match the observed value (Duerr, 2010). The Kuroshio Current Power is estimated based on numerical models (Kodaira, 2009).

4.2.2 Design of Ocean Current Turbines

Many different designs are possible for Rotor Nacelle Assembly (RNA) of OCT. As with wind turbines, horizontal-axis rotor is dominant in the marine current turbine concept, because vertical-axis rotors are subject to cyclic loading even in uniform flow, and will result in fatigue loads (Senat, 2011).

Installation sites of ocean current turbines are mostly deeper than tidal current turbine installation sites. The RNA is supported just below the sea surface by floaters, and moored to the seafloor. Additional supporting structures are not necessary (Suzuki, 2009b). A contra-rotating type concept has been investigated as a more efficient concept and compared with a twin-rotor type concept. The comparison results show that the power-weight ratio of the contra-rotating type and the twin-turbine type are almost the same, and the ratio is comparable to that of bottom-mounted wind turbines (Takagi, 2011).

5 OCEAN THERMAL ENERGY CONVERSION

Theoretically, OTEC is a vast source of energy that is virtually limitless and sustainable. With the energy produced by OTEC, hydrogen and oxygen can be produced by

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hydrolysis, the hydrogen and oxygen can then be liquefied, transported in cryogenic tankers to various destinations for use in space programs, fuel cell cars, industrial microchip manufacturing, power generation, etc. Fresh water can also be produced from seawater as a byproduct of the OTEC process, as the electric power produced during the process can also be used to power a reverse osmosis desalination process. Sea Water Air Conditioning (SWAC) has also been addressed for Pacific Ocean island buildings. Surface or small-depth sea water can be utilized as heat sources or sink for air-conditioning or heating by heat pump systems in temperate zones. High speed rail projects could very easily and efficiently be powered by alkaline fuel cell systems supplied by large-scale OTEC platforms (Energy Harvesting Systems, LLC, 2010). OTEC plants in the inter-tropical extraction belt could be considered to provide energy needed for oil and gas production, instead of burning a part of this production in thermal power plants.

5.1 Platform Design

The design of an OTEC platform depends on the weight and volume of the components on the structure, as well as the operating sea conditions. These platforms are usually quite large, in order to stabilize the structure against wave motion, improve its seakeeping performance, and reduce stress on the cold water pipe. Various designs of the OTEC platform and mooring systems have been considered by researchers over the past few decades. The simplest design is the rectangular barge type, such as the first MINI OTEC. The other four most complete OTEC design concepts offered in the 1980s were the spar OTEC plant by Lockheed Missiles and Space Co. (Trimble, 1975), the spar-buoy OTEC plant by Carnegie-Mellon University (Lavi, 1975), the submerged catamaran OTEC plant by the University of Massachusetts (Goss *et al.*, 1975), and the cylindrical surface vessel OTEC plant by TRW Inc (TRW Systems Group, 1975).

The grazing OTEC plant ship equipped with a propulsion system was proposed and designed by the Applied Physics Laboratory of Johns Hopkins University (Sasscer and Ortabasi, 1979). This OTEC plant is able to 'roam' the Pacific and Atlantic Oceans in order to seek for a high temperature differential. The OTEC tugboat concept was later proposed for the same purpose, but without the need to install a propulsion system. The surface ship design and the submerged cylindrical design have also been considered (Kamogawa, 1980) in order to meet the rough sea conditions around Japan.

A jacket-spar (J-spar) type of OTEC power plant was proposed by Srinivasan (2009) from Deepwater Structure, Inc. The J-spar configuration is able to suppress the alternate formation of Karman's vortex streets produced by underwater currents. Srinivasan (2009) also proposed the tension-based tension leg platform (TBTLP) in which an artificial seabed is utilized at an intermediate depth from the real seabed to support the TLP vessel tether system, thereby effectively enhancing the capacity of the tethers and reducing the sway and surge motion of the TLP.

5.2 Cold Water Pipe System

Ocean Thermal Energy Conversion platforms must have appropriate pipe technology to draw deep cold water for the process. The design, construction, and deployment of the cold water pipe (CWP) may be based on knowledge and experience gained from offshore risers. CWPs for OTEC plants are massive and subject to huge stresses at the joint between the cold water pipe and the OTEC platform. These stresses come from a combination of severe weather, wave action, and the length (more than $1000\,m$), diameter ($10\,m$ for a full-scale $100\,MW$ OTEC plant), and mass of the cold water pipe. It is worth noting that the Japanese have built a CWP (named TAKUMI) that upwells deep ocean water of $100{,}000\,m^3/day$ from $200\,m$ depth and discharges it into the euphotic surface level to enrich the nutrients, in order to increase fish production in the surrounding sea area (Ouchi, 2009).

5.3 Heat Exchanger System

A major cost of OTEC power plants lies in the heat exchanger. The most common heat cycle suitable for OTEC is the Rankine cycle, using a low-pressure turbine. Two main types of the Rankine cycle heat exchanger are used in OTEC – i.e. the closed Rankine cycle process and the open Rankine cycle process. The earlier design of the OTEC closed-cycle heat exchanger was of the shell and tube type. The Alfa Laval plate heat exchanger was successfully applied in the $50\,kW$ MINI OTEC pilot plant (Laboy *et al.*, 2011). Uehara of Saga University then developed a titanium plate-type heat exchanger (Uehara *et al.*, 1978). An experimental study for a $30\,kW$ OTEC plant using the Uehara cycle was carried out by Ikegami *et al.* (2008), where a new embossed plate heat exchanger functioning as an evaporator and a condenser was adopted to decrease the pump power.

Other types of working fluids were also considered in the closed-cycle system. By taking into account the size reduction of the heat exchangers and the piping cost, ammonia was found to be the best working fluid in the OTEC closed-cycle heat exchanger. Recently, experimental studies and dynamic model simulations were carried out to investigate the efficiency of the OTEC heat engine when the ammonia/water mixture is used as the working fluid (Ikegami *et al.*, 2008, Sathybhama and Babu, 2011, Wagar, 2010). Hans Krock has adapted the Kalina Cycle for OTEC in collaboration with Recurrent Engineering, the patent holders of the Kalina Cycle (Energy Harvesting Systems, LLC, 2010).

In contrast, the open-cycle system used the vacuum flash vaporization of warm water to drive a low-pressure steam turbine. In order to reduce the impact of released non-condensable gases during the vacuum flash-evaporation process, a pre-aeration chamber could be installed below the flashing chamber so that gas molecules could be removed before entering the steam turbine (Energy Harvesting Systems, LLC, 2010). Such design will result in more efficiency, as well as the environmental benefits of oxygenated discharge water. Additionally, it could prevent the discharge of carbon dioxide and other greenhouse effect gases into the atmosphere (Kong *et al.*, 2010). Srinivasan and Sridhar (2010) have also proposed an OTEC engine that uses subsea technologies, such as the subsea condenser, subsea pump, submerged evaporator, and independent floating-pipe buoy platform to transport working fluid from the turbine outlet to the subsea condenser.

6 SUMMARY AND CONCLUSIONS

Recent developments in offshore wind technology have led to the deployment of large-scale offshore wind farms based on bottom-fixed support structures. There have also been in the past few years a number of concept demonstrators of floating wind turbines. However, the primary focus and major challenge today is in capital and operational cost reduction, which requires substantial research work to achieve cost-effective design, especially with regard to support structures and foundations.

Although design rules for bottom-fixed offshore wind turbines are in development, design rules for floating wind turbines need to be initiated and should cover a large

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variety of floating concepts. Experience in the offshore oil and gas industry is valuable for such developments, but design requirements should be properly considered due to the unmanned nature of and economic constraints for fixed and floating wind turbines. Design tools, particularly rapid numerical tools for floating wind turbines need to be further developed and validated with model-scale and full-scale tests. In order to properly carry out structural design, these tools need to address not only aerodynamic and hydrodynamic loads, but also the structural responses of the rotor, tower and floating/mooring systems, as well as control strategy. In this respect offshore wind structural analysis can be more complex than for oil and gas structures however, machine loading can be monitored and controlled meaning greater scope for progressive life- cycle strategies.

Whereas to date monopole structures in relatively shallow waters (up to $40\,m$) have dominated, there is an increasing interest in jacket and tripod support structures for the $40 - 60\,m$ water depths particularly for the $5\,MW$ and larger structures. It should be noted that the structures installed to date have only been in operation for a relatively short period of time and not without some significant issues including integrity of grouted joints, internal corrosion and fatigue issues concerning transition pieces. The coming years will see a vast amount of field data and experience which will be important to learn from so that future designs can take full advantage of this experience and of the new emerging modelling techniques. In addition, focus will be on array optimization and cost reduction for large volume manufacture, deployment and operation.

The challenges associated with wave energy are similar or even greater than those associated with wind energy, mostly due to the wide variety of devices which have been proposed and to the fact that only a very few have been demonstrated in full scale. Although a larger number have been model-tested, many of these potentially good ideas have not been fully analyzed. Wave power has tremendous potential but for the moment is some years behind offshore wind. Cost reduction, particularly for moorings and deployment systems in addition to fatigue resistance are the primary challenges.

Tidal Stream is emerging rapidly as a serious commercial prospect with no fewer than ten large-scale concept turbine demonstrators since the last ISSC report. The predictability of the resource and relatively gentle manner in which turbines are loaded (compared to wave power) make it attractive. However the primary challenge is deployment in tidal flows greater than three metres per second and fixing to the sea bed. In this case the current costs of deployment and installation dwarf the cost of the supporting structure and it may be that tidal stream can only become economically competitive when array installations begin to use specially designed deployment vessels and machinery which have yet to be developed. Other issues are turbulence, resistance from debris and wake interaction effects, all of which are active areas of research and development. OCEC is related and is now receiving considerable attention; developments are likely to follow the Tidal Stream pioneering work as investments required are larger due to water depth and distance from shore.

Challenges for OTEC commercialization include its high cost, due to its large scale; finding an appropriate location that could leverage on the offshore oil and gas industry with respect to installation and specialized vessels, station-keeping systems, and support; and the concern over environmental risk (Cooper *et al.*, 2009, Cohen, 2009). Despite these challenges, it is reasonable that OTEC plants in one form or another will appear on our oceans.

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