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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. Aspects related to prototype testing and certification shall be considered.

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KEYWORDS

Offshore wind turbine, wave energy converter, marine current turbine, multiuse plat-form, design, integrated dynamic analysis, model test, field test.

CONTENTS

1. INTRODUCTION

This Specialist Committee V.4 Offshore Renewable Energy was first introduced to the ISSC in 2006. Since then, offshore wind technology has experienced a significant development, leading to commercial deployment of large-scale offshore wind farms. Extensive national and international research work has also been conducted regarding the development of Wave Energy Converters (WECs) and tidal and ocean current turbines. The ultimate goal, from both an academic and an industrial standpoint, is to develop cost-effective solutions for utilisation of offshore renewable energy. This report describes recent developments in this area with emphasis on research activities.

The subject of offshore renewable energy is highly multidisciplinary. In view of the relevance to the ISSC as well as the background and competence of the committee members, the focus of this report was naturally given to the marine aspects. However, when discussing the offshore wind technology, aerodynamic aspects are inevitably addressed because of the importance for design analysis. Similarly, Power Take-Off (PTO) systems and control are included in the discussion of wave energy converters, while issues of environmental impact and economic feasibility are discussed in the chapter of tidal and ocean current turbines. On the other hand, electrical aspects and grid development are omitted from the discussion in this report.

Chapter 2 presents a resource assessment for wind, wave and marine current energy; which is complementary to the information presented in the previous ISSC reports. The methodologies used for resource assessment, in particular the numerical models developed in recent years, are discussed in detail. Offshore wind technology is the most developed of the three areas considered and it is also the focus of this report. In particular, topics on numerical analysis and physical testing of Floating Wind Turbines (FWTs) are emphasised. Design rules and marine operations relating to transportation and installation of Offshore Wind Turbines (OWTs) are also discussed. The developments in wave energy converters and tidal and ocean current turbines are summarised in Chapters 4 and 5, respectively. A separate chapter is included to introduce some of the recent research projects on the integration of offshore renewable energy with other potential use of ocean space.

In Chapter 7, the main findings and conclusions from this committee are stated with respect to the different offshore renewable energy technologies. The challenges for developing cost-effective solutions are identified, and the recommendations for future work in this area are provided.

2. OFFSHORE RENEWABLE ENERGY RESOURCES

In the previous ISSC reports (ISSC (2006), ISSC (2009), ISSC (2012)), resources of offshore renewable energy (including offshore wind, wave, tidal and ocean current energy) were briefly introduced, with the key focus being European waters. This current report discusses the resources in other geographical areas around the globe. Moreover, detailed and accurate assessment of the resource for a given local area is very important for selection of the most suitable and cost-effective technology in the development of commercial offshore energy farms. It is crucial to reduce the uncertainty in the resource assessment normally conducted in the planning phase in order to improve the overall economics of an offshore energy farm. The numerical models and methods for resource assessment developed in recent years are discussed in detail.

2.1 Offshore wind energy resources

The North Sea is the centre for offshore wind development in Europe. The water depths in this region are not large, varying between 20m and 70m. The US maps illustrated in Figures 1 and 2 indicate the mean annual wind speeds at 90m above the surface, and the corresponding water depths at these locations. It can be seen that the water depths in most of the areas along the east and south coasts are moderate, while deeper waters in excess of 100m dominate the west coast and the Great Lakes areas. An average wind speed of at least 7m/s at this reference height is considered the minimum speed required for wind energy resource suitability. The estimated potentially extractable energy is around 4,150GW considering the areas within 90km from shore. Further details and information on the characteristics and validation methods were detailed by Schwartz et al. (2010).

The potential of wind power in Japan is estimated as 144GW for onshore generation and 608GW for offshore generation under the assumption that the offshore wind turbines are installed within 30km of the shore, in 200m water depths and under 7.5m/s of average wind speed at an 80m height. According to the Japan Wind Power Association (JWPA, 2012), this total offshore output is equal to around three times of the total output by all power generation facilities in the country. In Japan, there are aspects of the challenges regarding cost, technology, and social acceptance that differ widely from the natural and social environments and other conditions surrounding offshore wind power development in Europe. Consequently, it will be essential to utilize the proving research currently being advanced to establish low-cost offshore wind power generation technologies compatible with the conditions in Japan, according to the New Energy and Industrial Technology Development Organization (NEDO, 2013).

China has a long coastline which is a relatively rich resource for offshore wind energy. According to Qin et al. (2010), the technical potential is 1,322GW for the offshore area within 100km of the coast; with two-thirds of these areas located in shallow waters with depths from 10m to 50m. This is a similar energy density to that found in the North Sea.

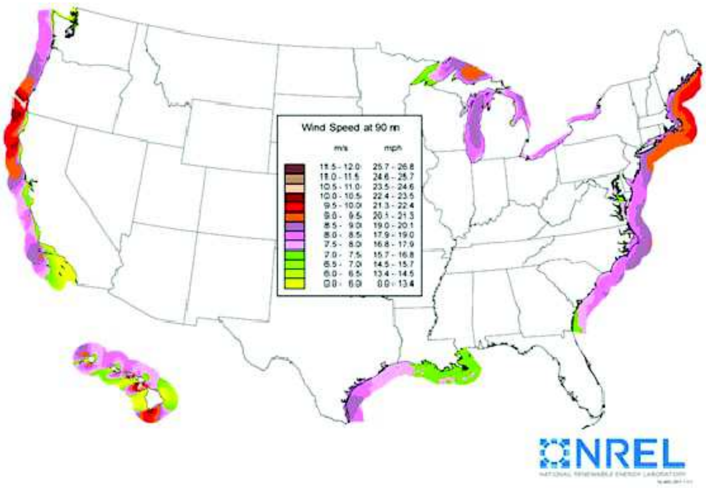

Figure 1. United States offshore wind resources (Schwartz et al., 2010).

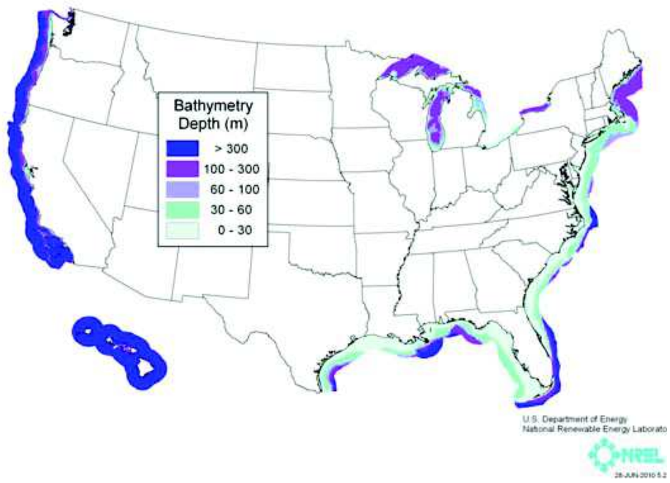

Figure 2. United States bathymetry distribution (Schwartz et al., 2010).

2.1.1 Resource assessment

The most commonly used tool for wind resource predictions, on land as well as offshore, is the Wind Atlas Analysis and Application Program (WAsP). WAsP is a computer program developed for predicting wind climates and power productions from wind turbines and wind farms. Another method to predict the wind resource is the mesoscale meteorological model (MM5). A comparison of these two methods was carried out in 2007 for the German Bight by Jimenez et al. (2007).

A method of estimating the annual wind energy potential of a selected site using short-term measurements related to one year's recorded wind data at another reference site was published by Bechrakis et al. (2004). They summarized a method which offers a reliable prediction of the wind potential of an area using only short time period measurements in combination with longer term wind measurements of a nearby station. The errors in the mean value estimation are tolerable and fall within the expected percentages of uncertainty with respect to the annual variation of the wind conditions in an area.

As per Bechrakis et al. (2004) and Jimenez et al. (2007), it is important for an acceptable prediction of the wind resource to know the climate conditions at the points of support for the prediction. For example, an operational wind forecast system for the Portuguese pilot area of Aguçadoura was presented by Salvacao and Guedes Soares (2014).

Furthermore, some results regarding high-resolution reanalysis data and floating met-mast measurements at deep-water locations influenced by coastal topography were summarized by Del Jesus et al. (2014). Motion effects on Lidar (Light detection and ranging) wind measurement data of the EOLOS buoy were highlighted by Bischof et al. (2014).

2.2 Wave energy resources

Figure 3 illustrates a map of global annual mean wave power (Mørk et al., 2008). It was based on the data from the ECMWF WAM model archive and calibrated and corrected by Fugro OCEANOR against a global buoy and Topex satellite altimeter database. This map indicates that the highest average levels of wave power are found on the leeward side of temperate zone oceans due to the origins of oceanic wind (and inherently waves), in particular, between 40° and 60° in both hemispheres.

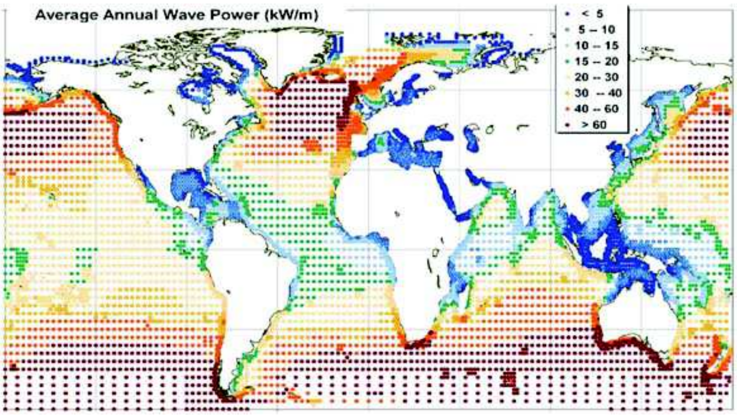

Figure 3. Global annual mean wave power estimates in kW/m (Mørk et al., 2008).

High resolution numerical models are useful for resource assessment of a specific site. The FP7 EquiMar project (http://www.equimar.org/) has delivered a suite of "high level" protocols–general principles to enable fair comparison of marine energy converter testing and evaluation procedures. In particular, Venugopal et al. (2010) provided a full description of the numerical methods used for the wave resource assessment. These methods can be divided into two categories: 1) the deterministic approach, which describes the sea surface evolution accurately in both time and space; and 2) the spectral approach, which provides a statistical description of the wave conditions in space and time. The best deterministic models are able to capture all the relevant physics of wave/bottom/shoreline and non-linear wave-wave interaction, but they are relatively computationally expensive. In practice, spectral methods are more commonly used to characterize the sites of interest. Available spectral methods have reached their third generation and provide an approximate description of the physical effects associated with nonlinear wave-wave interaction, wind input, and wave-breaking/bottom dissipation modelled as source terms.

Even though most of these numerical models are open-source and user-friendly their accuracy and reliability depends on the skill of the user, the computational power available and the accuracy of the input data. For example, Strauss et al. (2007) compared the wave prediction along the Gold Cost of Australia with two of these solvers MIKE 21 (MIKE-21 (2008), Johnson (1998)) and SWAN (SWAN, 2009). Both the models were shown to over-estimate the significant wave-height for high wind speed, highlighting the importance of the correct input data of the wind field.

Venugopal et al. (2011) also produced a report for EquiMar which shows a comparison between the models MIKE21, SWAN and TOMAWAC (2014), for the wave prediction along the Figueira da Foz coastline in Portugal. The correlation coefficients obtained between the measured buoy data and the wave model output for various wave parameters are above 0.8 for each of the models, indicating a very good correlation. However, the same authors pointed out that Figueira da Foz is a rather simple location (the bathymetry is smooth and the coastal geometry is nearly linear); which explains the good agreement between the model results and measured data, despite the use of coarse bathymetric data. Nonetheless, there are a few differences between three model's outputs which could be attributed to slightly different formulations and input model parameters (coefficients) selected for the simulations.

For verification of numerical models against measurement buoy data for local wave resource assessment, it is essential to compare statistical distributions (rather than only basic statistics) of relevant parameters (Edwards et al., 2014a) and to compare spectral values (Edwards et al., 2014b). Such level of comparison is important to determine the reliability of and to reveal some potentially vital issues in the numerical models for prediction of wave energy extraction.

In Liberti et al. (2013), the WAM solver (Günther and Behrens, 2011) is used for the prediction of wave energy, heights, periods, directions, seasonal and inter-annual variability in the Mediterranean Sea. The fine spatial resolution of the solver and the good accuracy in the modelling of the bathymetry and of the wind-field allowed a remarkable comparison with wave buoy data over a ten year period. On the website http://utmea.enea.it/data/waves, the same authors displayed the results of the Operative Model WAVES for the next five days of hourly forecasts for the Mediterranean Sea. The model is based on a nesting between WAM used for the whole basin at 1/32° resolution, approximately 3 km, and SWAN that zooms in to ten interesting areas at 1/200° resolution, approximately 800m.

Even when accurately and carefully handled, these models cannot completely describe the evolution of the free surface and the kinematics of the wave field. It is now common practice to equip wind turbines with Lidars to measure the speed and direction of the incoming wind, and it would be similarly beneficial for WECs to have a means of "now-casting" the incoming waves to better position themselves (Cagninei et al., 2013) or control the PTO settings (Sjolte et al., 2013). Although the description of the wave energy resource is most relevant at the design stage when the features of the WEC are tuned to the exploitation site, now-casting could become a means to improve productivity once the technology has advanced to the fully commercial stage. A tool that may make this possible is SNOW, which is derived from ship science where the now-casting represents a critical feature for the landing of aeroplanes or helicopters on ships (Xiao et al. (2009), Yue and Solodonz (2008)).

2.3 Tidal and ocean current energy resources

Resource assessment is important and critical for marine current turbines to estimate energy yield and evaluate extreme design conditions. The tidal and ocean current energy resources are strongly site-dependent. The understanding of in-situ flow conditions can be derived from a combination of numerical modelling and survey data. Goundar and Ahmed (2014) performed a resource assessment and turbine blade design for Fiji according to measurement of flow velocities, flow direction, wave height, wave frequencies, and velocity profiles. Bahaj (2013) showed a site measurement of flow conditions close to Alderney, Channel Islands, UK. Kim et al. (2012a) have assessed the ocean renewable energy resources in Korea, concluding that tidal energy is likely to play an important role in their future energy mix. Several, initially less energetic, sites around the globe are now attracting interest for development: these include the southern coast of Iran (Rashid, 2012); the Aleutian Islands, Alaska (Wright, 2014); the Puget Sound, USA (Polagye and Thomson, 2013); the Shannon Estuary, Ireland (O'Rourke et al., 2014); Roosevelt Island, New York, USA (Gunawan et al., 2014).

2.3.1 Physical resource assessment

The flow conditions in an area with a large or strong tide are complex and physical assessment is often imperative to assess the resource and determine the appropriate locations for various devices. Acoustic Doppler Current Profilers are frequently used (Thomson et al. (2012), Polagye and Thomson (2013), Stevens et al. (2012), Palodichuk et al. (2013), Bell et al. (2012), O'Rourke et al. (2014), Gunawan et al. (2014)) both bottom mounted and on floating vessels or platforms. A common observation in various locations around the globe is the presence of large scale, anisotropic eddies dominating the energy spectra. Marine radar has also recently been utilised to determine surface currents at a few locations (Bell et al., 2012) with a good level of success. Ultimately, the temporal variation of the current speeds, current directions, turbulence intensities, and power densities attained through physical measurement provides essential data for device, structure and array development with respect to uncertainties in energy yield and structural fatigue.

2.3.2 Numerical resource modelling

Physical modelling of resources is both time consuming and costly, therefore numerical assessment of resources is desirable to bring down both timescales and overall project costs. With the complexities in flow conditions evident at tidal sites this is not a trivial matter. Large scale oceanographic models are well developed (Yang et al. (2013), Kelly et al. (2012), Taguchi et al. (2014)) but tend not to capture the local convolutions apparent in tidal races.

Two dimensional modelling is common, and well-practised in oceanography, and several have been further developed to incorporate various aspects specific to tidal sites. Easton et al. (2012) showed that 60% of incoming tidal energy is dissipated via friction with the local environment in an energetic tidal channel.

Three dimensional modelling is generally required in order to capture the erratic nature of tidal energy sites for proper assessment and analysis for project development. Venugopal and Nemalidinne (2014) indicated that a coupled 3D wave and tidal model performed well when compared to ADCP data for the waters in the Pentland Firth. Pacheco et al. (2014) also used a combination of numerical modelling and physical measurements for the Faro channel in the Ria Formosa, Portugal. The results indicated that the channel would be a good test site for HATTs with power densities in the region of 5.7kW/m2 in currents of 2.2m/s. It is stated that the methodology can be adapted for application to any other intel-tidal channel or estuarine mouth. Ultimately, it is agreed that 3D models should be validated with data attained through physical test methods (Work et al. (2013), Tang et al. (2014)).

Of particular interest is the Semi-implicit Eulerian-Lagrangian Finite-Element (SELFE) model used by Behera and Tkalich (2014). The model solves the 3D shallow water equations with Boussinesq approximations. The model was used to assess the potential for tidal energy extraction in the Singapore Strait, and concluded that a theoretical array could produce in excess of the 4% of the energy demand for Singapore.

3. OFFSHORE WIND TURBINES

3.1 Recent industry and research development

Development of demonstration and commercial offshore wind farms

Since 2008, offshore wind industry has experienced a significant growth in installed capacity, especially in Europe. According to International Energy Agency (IEA, 2014a), the total installed offshore wind capacity by end of 2013 reached 6,590MW from the 11 IEA Wind member countries and 2,011MW of the total new capacity was added during 2013 (Table 1). A high average annual increase of about 35% is also observed during recent years (2011–2013).

Table 1. Cumulative Installed Capacity (MW) of Offshore Wind Power 2011–2013 (IEA, 2014a).

Country	2011 Capacity	2012 Capacity	2013 Capacity
United Kingdom	1,838	2,679	3,653
Denmark	871	920	1,271
Germany	200	280	903
China	108	390	428
Netherlands	228	228	228
Japan	25	25	50
Finland	26	26	26
Ireland	25	25	25
Korea	0	2	2
Norway	2	2	2
Portugal	2	2	2
Total	3,325	4,579	6,590

Among these developments, Europe is the major player, accounting for 96.9% of the newly installed capacity in 2013 and 92.7% of the total installed capacity by end of 2013. In terms of the cumulative installed capacity in different European countries, the UK has a share of 56% by end of 2013, followed by Denmark 19%, Belgium 9%, Germany 8%, Netherlands 4% and Sweden 3%.

According to European Wind Energy Association (EWEA, 2014), a monopile is still the most popular support structure for bottom-fixed offshore wind turbines, with 75% of the substructures in European waters being monopiles, 12% gravity-based foundations and 5% jackets.

However, as the International Energy Agency (IEA, 2013) indicated, the investment costs for offshore wind can be two to three times higher than onshore wind developments due to the additional expense associated with substructures, electric infrastructure and on-site installation. Moreover, the recent offshore wind development also resulted in an increase in the capital cost per unit installed capacity, Figure 4. This is because more and more wind turbines are being installed in deeper waters, further away from shore. The main challenge for offshore wind is cost reduction and this is also true for development of alternative offshore renewable energies.

Therefore, the tendency in offshore wind industry is to increase the size of individual turbines, as well as the size of wind farms, in order to reduce the installation and maintenance costs. The average rated power of offshore wind turbines increased from 3MW in 2008 to 4MW in 2013 and the average wind farm capacity was around 485MW per wind farm in 2013.

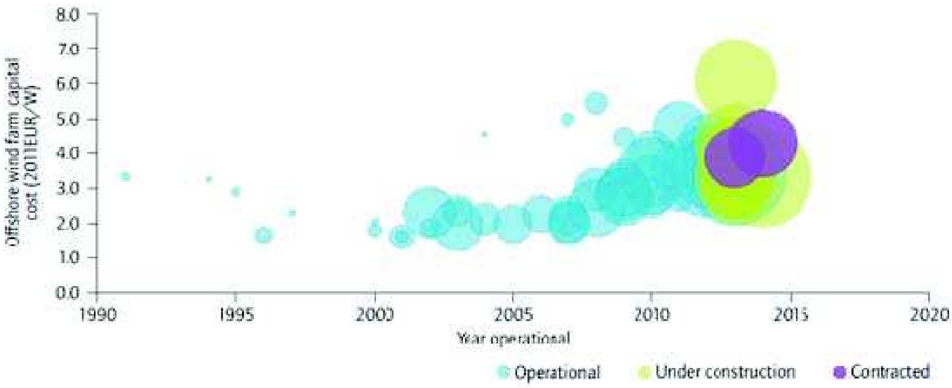

Figure 4. Capital costs (EUR/W) of European offshore wind farms by year (IEA, 2013) (The figure was reproduced by IEA, with the source from GL Garrad Hassen. The bubble diameter indicates wind farm capacity.)

According to the European Commission (EC, 2008), the EU has set a target for offshore wind development, to achieve 40GW of installed capacity by 2020 and 150GW by 2030, which is equivalent to 4% and 14% of EU electricity demand, respectively. This implies a significant amount of marine operations related to transportation and installation of wind turbine components in the European waters in the next five years. Considering 4MW wind turbines, more than 1000 units will need to be installed every year. However, the trend to develop and deploy large-scale wind turbines (6-8MW) would help to reduce the total number of operations at sea.

While there are no commercial offshore wind farms operating in the United States as of this writing, there are several projects at advanced stages of planning. Cape Wind in Nantucket Sound near the coast of Massachusetts has plans for the construction of 130, 3.6MW, offshore wind turbines scheduled to begin in 2015. Initial stages of construction have also begun on Deepwater's Block Island off the Rhode Island coast. The Block Island Wind Farm has plans for a 30MW development consisting of 5 turbines. In May 2014, the US Department of Energy (DOE, 2014) selected three demonstration projects for additional funding to achieve commercial operation by 2017. Among them, Dominion Virginia Power will test two 6MW direct-drive wind turbines on twisted jacket foundations, while Fishermen's Energy of New Jersey will install five 5MW direct-drive wind turbines also on twisted jacket foundation. Principle Power are to install five 6MW direct-drive wind turbines on their semi-submersible floating foundation–WindFloat.

The offshore wind development in China has been slow (Korsnes, 2014) since the first major offshore wind farm, Donghai Bridge 102MW installation, was completed off Shanghai in 2010. With the second major wind farm of 150MW (Phase 1 and 2 of the Rudong Intertidal wind farm) completed, the total installed offshore wind capacity reached 428.6MW by the end of 2013. On the other hand, according to the 12th 5-year Plan for Renewable Energy, the Chinese Government's goal is to achieve 5GW of installed offshore wind power by 2015, and 30GW by 2020. However, there is some uncertainty as to whether the 2015 goal can be achieved (Korsnes, 2014).

In Japan, only 50MW of the total offshore wind capacity was installed by end of 2013, including two 2MW floating wind turbines. In 2015, another two 7MW floating wind turbines (one on an advanced spar with heave plates and the other on a V-shape semi-submersible) will be deployed in the Fukushima area as part of the Fukushima Floating Offshore Wind Farm Demonstration Project run by Fukushima Offshore Wind Consortium (FOWC, 2011). In the long term, the Japan Wind Power Association (JWPA, 2014) has set up a roadmap to install 700MW of wind power offshore (100MW on floating foundations and 600MW on bottom-fixed foundations) by 2020 and 10GW (4GW floating and 6GW bottom-fixed) by 2030.

Development of floating concepts

Floating wind turbines have been proposed and developed in recent years, but there are no commercial farms yet. The Cost of Energy (COE) is much higher than that of offshore bottom-fixed wind turbines, due to costly support structures. Experiences regarding design, installation and operation of floating wind turbines are now being gathered through prototype tests. Three different methods for floating platform foundation are defined by Butterfield et al. (2005)–ballast, buoyancy (weighted waterplane area) and mooring line stabilisation. A comprehensive overview of various global floating foundation development projects is provided by both Bossler (2013) and Arapogianni and Genachte (2013).

Statoil installed the world´s first floating offshore foundation, the Hywind spar buoy, in 2009 which supports a Siemens 2.3MW wind turbine (Statoil, 2014), Figure 5(a). A semi-submersible floating platform, WindFloat, was launched with a 2MW Vestas turbine on board in 2011 (PrinciplePower, 2014), Figure 5(b). Two Japanese floating foundations were commissioned, and subsequently installed, in the second half of 2013. The semi-submersible foundation by Mitsui with a Hitachi 2MW downwind turbine (FOWC, 2013), Figure 5(c), and a hybrid spar floating offshore wind turbine developed by a Kyoto University and Toda Corporation with a Hitachi/JSW 2MW turbine (GOTO-FOWT-Website, 2014) have been in operation since late 2013, Figure 5(d).

Figure 5. Prototypes of floating wind turbines (from left: a) Hywind (Statoil, 2014); b) WindFloat (PrinciplePower, 2014); c) Fukushima semi-submersible (FOWC, 2013); d) GOTO spar (GOTO-FOWT-Website, 2014)).

Other buoyancy stabilised ideas are in the phase of conceptual design, such as the IDEOL platform (http://www.ideol-offshore.com/en/floater_overview), which is a ring-shape surface concrete floater with a shallow draught and compact dimensions. Some have reached a more detailed level of development such as the three column Mitsubishi structure intended for deployment with a 7MW turbine on board. This platform has been fabricated and is planned for installation in 2015 (FOWC, 2011).

The last floating foundation concept, with several installed at sea and in operation as prototypes at small scale, is the Tension Leg Platform (TLP). Such concepts for floating offshore wind turbine support structures are currently at various stages of development. Iberdrola's TLP solution comprises a single central body as per Rodriguez et al. (2014), Figure 6(a). Glosten Associates have developed a similar concept, the PelaStar structure (Scott, 2013), Figure 6(b). Following the same principals as a TLP the Tension Leg Buoy (TLB) has also been explored. A TLB (Myhr and Nygaard, 2012) has significantly lower steel mass in comparison to other platform types that can be deployed in water depths of 50m and more, Figure 6(c). However, the mooring line configuration and associated buoyancy distribution results in higher horizontal loads when compared to a conventional TLP mooring spread. The angled TLB mooring spread (Lee (2005), Myhr and Nygaard (2012)), is also utilised by the GICON-TLP (Adam et al., 2014).

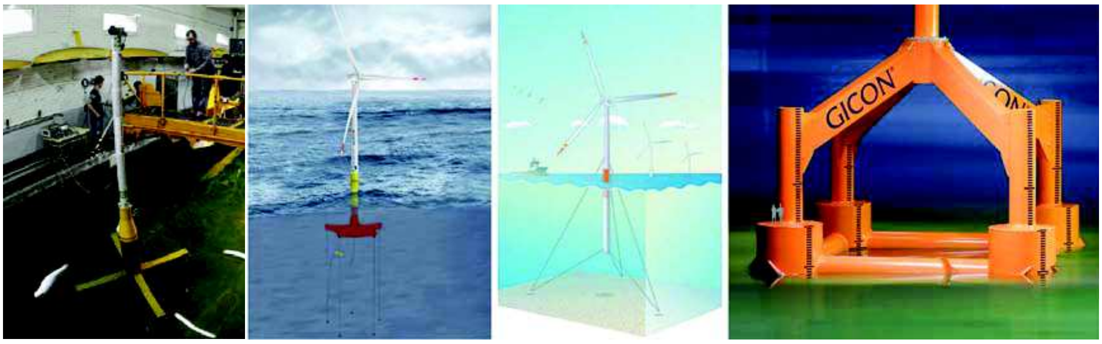

Figure 6. Concepts of TLP or TLB floating wind turbines (from left: a) Iberdrola TLP (Rodriguez et al., 2014); b) Glosten PelaStar TLP (Scott, 2013); c) TLB concept (Myhr and Nygaard, 2012); d) GICON-TLP (Adam et al., 2014)).

The concepts discussed above are floating platforms supporting one Horizontal Axis Wind Turbine (HAWT). Vertical Axis Wind Turbines (VAWTs) on floating foundations were also studied in recent years. In addition, floating concepts with multiple turbines have also been proposed. A small-scale multiple turbine, hexagonal floating platform for an offshore wind power plant was installed in Hakata bay by Kyushu University on December, 2011 (Bossler, 2013). The platform is 18m in diameter and has a displacement of 140ton supports two 3kW wind turbines equipped with Flanged-Diffuser and solar panels rated to 1.5kW. The platform is supported by six vertical cylinders connected by a truss. The hydrodynamic forces and moments in waves were determined using interaction theory for multiple floating bodies. Extreme environmental loading, wind and wave, needs to be considered when designing platforms for safety and through-life performance. CFD (Computational Fluid Dynamics) has been undertaken and is being developed for the multibody platform, ready for comparison with results attained from model tests under both wind and waves. In this manner the principal dimensions were confirmed. The project subsequently intends to undertake a verification test with two 200kW wind turbines equipped with flanged-diffusers and solar panels rating up to 100kW on a 100m diameter, hexagonal platform floating in the ocean.

3.2 Numerical modelling and analysis

3.2.1 Numerical tools–state-of-the-art

In order to develop cost-effective solutions of offshore wind turbines, uncertainties associated with the estimation of loads/load effects in the design phase should be reduced. This requires accurate numerical methods for dynamic response analysis. Offshore wind turbines are designed and analysed using simulation tools which allow an account of the coupling effects between aerodynamics, hydrodynamics and elastic responses as well as control of the turbine. Therefore, incident waves, sea current, hydrodynamics and dynamics of the support structures should be considered in line with wind turbine loads as per Jonkman and Musial (2010). Several integrated tools exist to simulate dynamic behaviour of offshore wind turbines, both bottom-fixed and floating.

Integration of onshore wind technology and the technology developed in the offshore oil and gas industry has resulted in a significant development of numerical tools for analysing offshore wind turbines. These integrated tools (Jonkman and Musial, 2010) are developed either from the numerical codes for onshore wind turbines by adding hydrodynamic modules, such as FAST, HAWC2, Bladed, 3DFloat, or from a hydrodynamic and response analysis code coupled to a wind turbine aerodynamic module, such as Simo-Riflex-AeroDyn.

As reported in ISSC (2012), the IEA initiated two benchmark studies on most of these tools–the Offshore Code Comparison Collaboration (OC3) and Offshore Code Comparison Collaboration, Continuation (OC4). The purpose of the OC3 and OC4 projects was to verify the accuracy of offshore wind turbine simulation tools via a code-to-code comparison of simulated responses of various offshore structures (Vorpahl et al. (2014), Robertson et al. (2014)). The OC3 project considered monopile, tripod and spar wind turbines; while a jacket wind turbine and a semi-submersible wind turbine were studied in the OC4 project.

As a further continuation, the ongoing OC5 project (Offshore Code Comparison Collaboration, Continuation, with Correlation) focuses on the validation of numerical tools against model tests or field measurements over three phases. In the first two phases, the model test results of hydrodynamic loads on a fixed cylinder and responses of a semi-submersible floating wind turbine are to be considered. The field measurements of a jacket wind turbine will be used in the last phase.

3.2.2 Load and response analysis of bottom-fixed wind turbines

3.2.2.1 Integrated dynamic analysis and fatigue assessment

Reliable power production from a wind turbine is one of the key factors contributing reduction in the cost of energy. Providing adequate reliability can help reduce the need for costly repairs and downtime. Most of the shallow water offshore wind turbines are installed on bottom-fixed substructures such as monopiles, concrete gravity bases, tripods or jackets. Water depth plays an important role to find a cost-effective solution for foundations. Although the current industrial practice for design of bottom-fixed wind turbines still relies on a decoupled analysis approach with wind turbines and foundations designed by different companies, integrated analysis methods and tools have been developed (see Section 3.3.1) and should be soon applied in the industry for structural design and power output estimation.

Bagbanci et al. (2012a) studied the influence of the environmental conditions on wind turbine design loads for a monopile foundation using aero-servo-hydro-elastic code. Detailed analysis regarding the bending moment at the tower base and blade root for various values of water depth, tower height, pile diameter and differing turbulence model was presented. The maximum blade bending moment was observed to increase with wind speed up to the rated wind speed of 11.5 m/s, and then decrease. However, for each case the bending moment at the tower base is at a maximum for 30m and minimum for 10m of water depth.

Shirzadeh et al. (2013) performed an aeroelastic simulation of a Vestas V90 3MW wind turbine using the HAWC2 aeroelastic code. The Operational Modal Analysis was used to identify the damping value of the fundamental fore-aft mode of an offshore wind turbine using both real life measurements and simulations. It was observed that the estimations of the total damping of an offshore wind turbine gave a quantitative view of the stability characteristics of the wind turbine.

In the offshore oil and gas industry, fatigue criteria have been of key concern for fixed offshore platforms since the early 1970s. It is an important consideration for the design of structures in areas with repetitive hydrodynamic loading, storm conditions and especially for dynamically sensitive structures. For offshore wind turbines, dynamic response under resonance is more significant than that of traditional platforms used in the offshore petroleum industry due to the wind loading effect. The fatigue load and the number of load cycles to be considered are much higher than those associated with a more traditional platform. Thus, the fatigue performance of welded connections is a design-driving criterion for offshore wind turbine support structures. On the other hand, long-term fatigue analysis requires a large number of simulations considering different combinations of wind and wave conditions. This creates a requirement for efficient yet accurate analysis methods.

Long and Moe (2012) performed a frequency domain analysis for a lattice type bottom fixed offshore wind turbine. The 5MW NREL (National Renewable Energy Laboratory) wind turbine installed in water of depth 35m was redesigned with respect to the Fatigue Limit State (FLS) for three-legged and four-legged lattice towers. It was observed that the lattice towers designed in accordance with the ultimate limit state could not meet the fatigue requirements, notably at the joints. In other words, the fatigue limit state is the governing design criterion. In comparison with designs based upon ultimate strength, the mass of both types of towers increased by maximum 30%.

Dong et al. (2012) presented the dynamic response of a jacket support structure due to wind and wave loads, and predicted the fatigue reliability of welded multi-planar tubular joints of the same structure. A site in the northern North Sea with a water depth of 70m was considered and the hot-spot stress approach was used for fatigue analysis of failure-critical location of the related reference braces of the selected tubular joints.

Yeter et al. (2014a) and Yeter et al. (2014b) developed a methodology by employing the finite element method for coupled dynamic analysis in frequency domain, which indeed allowed performing more sophisticated response analysis by the means of modelling of a tubular structural system by shell elements. Yeter et al. (2015a) investigated the influence of the overload on the retardation under various load cases that are specified by factors of retardation.

Detection of damage in the members of support structures prior to a catastrophic failure is also an important area for investigation. Liu et al. (2014a) proposed an improved modal strain energy method for damage localisation in jacket-type offshore wind turbines. The method defined a series of stiffness-correction factors that could be employed to calculate the modal strain energy of the measured model without utilising the stiffness matrix of the finite element model as an approximation. The numerical studies indicated that the proposed method significantly outperformed the traditional modal strain energy and modal strain energy decomposition methods, especially for damage location.

3.2.2.1.1 Ice-induced load and response analysis of offshore wind turbines

Support structures for offshore wind turbines in cold climates are subject to ice actions that add risks and increase costs of construction and maintenance (Salo and Syri, 2014). Facilities in the Baltic and the Gulf of Bothnia, for example, must be designed to withstand static and dynamic ice loads (Hirdaris et al., 2014). Popko et al. (2012) made an in-depth comparison for the available design standards for offshore wind turbine support structures subjected to sea ice loads. The IEC standard 61400-3 provides several Design Load Cases (DLCs) for consideration, as do standards such as DNV-OS-J101 (Sirnivas et al., 2014). Both parked and power production modes are considered. Ice load scenarios must be addressed for horizontal and vertical ice forcing from thermal expansion as well as ice floe impact, cyclic loading from ice crushing, and pressure ridge encounters with support structures. Design scenarios and basic design approaches for ice resistance are influenced by knowledge obtained from arctic offshore structures (ISO (2010), Thomas and Graham (2014)).

As is the case for offshore oil production structures located in cold climates, the magnitude of ice loads may be of the same order as wind and wave loading; in fact ice action may dominate in some situations (McGovern and Bai (2014), Hou and Shao (2014)). Serious ice induced vibrations of offshore structures have been seen to occur; for example in the Bohai Sea and Bothnia Bay (Xu et al., 2014). Severe vibration conditions can arise at certain impact velocities in which the breaking patterns of the ice occur at a frequency which matches the structural vibrations modes (Bjerkås et al. (2013), Bjerkås et al. (2014), Xu et al. (2014)). This condition is referred to as frequency lock-in and is specifically addressed in the IEC and ISO standards and class society guidelines. Frequency lock-in is important for determination of force and displacement magnitudes and also the number of vibration cycles for fatigue assessments (Hendrikse et al., 2014).

Ice loading is stochastic in nature (Zvyagin and Sazonov, 2014) and average ice pressures depend upon contact area as well as the failure mode of the ice, which is in turn influenced by the ice and structural geometry (Bekker et al., 2013). Local pressures are generally lower than global forces (Spencer et al., 2014) and probabilistic descriptions of these effects have received considerable attention (Taylor and Richard, 2014). These effects also play important roles in analysis of impact forces from level ice features and pressure ridges (Molyneux et al. (2013), Norouzi et al. (2013)).

Conical structures located on the turbine support structure in the ice belt region are used for reducing ice force magnitudes and ice-induced structural vibrations (Barker et al., 2014). Both upward and downward sloped cones have been considered, each having a tendency to cause the ice to fail in bending rather than crushing and thereby reduce the forces acting on the structure (Xu et al., 2014).

New advanced structural dynamics modelling capabilities have been developed to incorporate combined loading from wind, wave and ice in a finite element model (Hilding et al., 2012) and time-domain simulation of wind turbine response. The simulation software FAST, developed by the National Renewable Energy Laboratory, has a new modular framework which includes capability for modelling multimember substructures (Song et al., 2013). New modules covering ice loading capability are also being integrated (Yu et al. (2013), Yu et al. (2014), Barahona et al. (2015)).

3.2.2.2 Challenges for design and analysis of bottom-fixed wind turbines

Grouted connections

A grouted connection forms the connection between the transition piece and the monopile in offshore wind turbine structures.

Such connection has been subjected to intensive research during the last couple of years based on experiences in the offshore wind industry. It was found that an acceptable level of safety was not reached with existing design methods, developed for traditional jacket structures that mainly are subjected to axial loading. This was based on the fact that stresses in a monopile caused by bending moments from wind loading can be more than one order of magnitude larger than those due to the axial load alone (Lotsberg et al. (2012a), Lotsberg et al. (2013)).

DNV initiated two joint industry projects (JIPs) on grouted connections. The first was carried out from 2009–2011 to investigate the structural capacity of grouted connections made without using shear keys, which have been the most common solution for monopiles. The second project was initiated in 2011, studying the capacity of cylindrical shaped grouted connections with shear keys (Lotsberg et al. (2012b)).

The JIPs have resulted in the development of a new design methodology to account for large dynamic bending moments on monopiles, and updates of the existing design standards.

Soil-pile interaction

The method commonly adopted in design codes for analysis of laterally loaded piles is denoted the p-y approach and is based on the Winkler model. It has been a successfully proven method in the offshore oil and gas industry. However, it has not been shown to be suitable for predicting responses for monopiles with large diameters and loads that need to be accounted for in the offshore wind industry. Further research in this direction is required.

The PISA project (Pile Soil Analysis project) (http://www.eng.ox.ac.uk/geotech/research/PISA) is a research project that is focusing on developing new and improved design methods for laterally loaded piles, specifically targeting monopile foundations. The project is led by Dong Energy and run through the Carbon Trust's Offshore Wind Accelerator programme. Onshore field tests were performed in 2014 to assess the lateral response of monopiles in soils considered as representative for the North Sea, in both sands and clays, involving piles with a diameter of approximately 2.1m.

Negro et al. (2014) identified the uncertainties compromising offshore wind farm structural design and which were the design of the transition piece and the difficulties regarding characterisation of soil properties. Alternative design criteria were proposed using heterogeneous soil characteristics, considering the risks related to the requirement of considerable investment and time for a full soil campaign.

Damgaard et al. (2014) performed a numerical investigation based on nonlinear Winkler foundation models. Experimental tests were carried out in order to evaluate the eigen-frequencies related to the lowest eigen-mode of offshore wind turbines. The study showed that the permeability of the subsoil has a strong influence on the stiffness of the wind turbine; and that this may, to some extent, explain the deviations observed between experimental and computational eigen-frequencies.

Similarly, eigen-frequencies and therefore dynamic characteristics of monopile wind turbines will alter due to the presence of scour. Myrhaug and Ong (2013) studied the scour around vertical pile foundations of offshore wind turbines resulting from long crested (2D) and short crested (3D), nonlinear, random waves. A stochastic method was used to derive the maximum equilibrium scour depth around the piles exposed to the wave climate. The approach was based on the assumption that the waves were a stationary narrow-band random process and adopted the Forristall wave crest height distribution.

Structural reliability analysis

In recent years, fatigue reliability assessments have been performed for different types of wind turbine support structures; monopiles, jackets and tripods (Sørensen (2012), Dong et al. (2012), Lee et al. (2014), Yeter et al. (2015b)). As highlighted by Dong et al. (2012), future research needs to focus on the identification and quantification of model uncertainties associated with external load analysis, dynamic response assessment and fatigue damage calculation.

Mardfekri and Gardoni (2013) developed probabilistic models to predict the deformation, shear and moment demands on offshore wind turbine support structures subject to operational and environmental loadings. The proposed models were then used to assess the fragility of an offshore wind turbine subject to day-to-day wind, wave and current loading. The conditional probabilities of exceeding the specified performance levels were found to increase with the average wind speed, up to the rated wind speed.

Based on a sensitivity analysis performed by Yeter et al. (2015b) for a tripod offshore wind turbine, it was found that the uncertainty associated with wind loading dominates over that of wave loading in a fatigue reliability assessment. For bottom-fixed offshore wind turbines, wind-induced dynamic responses are much larger than wave-induced responses.

Thöns et al. (2012) has established the model basis regarding the ultimate limit state consisting of structural, loading, and probabilistic models of the support structure of offshore wind energy converters together with a sensitivity study. The model basis is part of a risk based assessment and monitoring framework, and is applied to determine the reliability as prior information for the assessment and as a basis for designing a monitoring system.

3.2.3 Load and response analysis of floating wind turbines

3.2.3.1 Design aspects and analysis methods for floating wind turbines

As mentioned in Section 3.1 three primary foundations were defined for floating offshore wind turbine support structures: spar, semi-submersible and TLP. Thiagarajan and Dagher (2014) presented a brief review on the concepts of offshore floating platforms. The key studies considering floating foundation structures for offshore wind were described. The simulation tools and experimental studies were discussed to assist development of sustainable solutions. A detailed review of offshore floating wind turbine concepts is also presented by Bagbanci et al. (2012b) and Guedes Soares et al. (2014a).

Bachynski and Moan (2012) discussed the design requirements for TLP structures with respect to five key aspects:

- the natural periods for surge and sway motions longer than 25s;
- the heave, roll and pitch natural periods less than 3.5s;
- the largest mean offset not exceeding 5% of the water depth;
- the minimum tendon size according to the ULS (Ultimate Limit State) design;
- and the minimum displaced volume of 2000m^3.

Five baseline TLP designs supporting the NREL 5MW wind turbine were derived in their study, with the displacement ranging from 2330m^3 to 11866m^3. Dynamic response analyses for assessment of the designs were carried out using the coupled code Simo-Riflex-AeroDyn. A practical, single column, TLP design with displacement ranging from 3500-6500m^3 was developed, incorporating three pontoons, with a pontoon radius of 28-35m. Such a platform may be capable of supporting the NREL 5MW wind turbine safely in harsh environmental conditions.

A semi-submersible concept is likely to be more competitive in shallower waters when compared to the spar and TLP concepts. A version of the WindFloat semi-submersible, proposed by Roddier et al. (2009), has been under test in open water since 2011. In a comparative study between a generic WindFloat (4500ton) and a generic spar (7500ton) supporting a 5MW wind turbine (Roddier et al., 2011), the hydrodynamic performance of these two concepts was found to be similar; however WindFloat, being equipped with heave plates, exhibits improved overall response. WindFloat also facilitates installation and commissioning techniques, with the whole system being assembled at the quay side and then towed to the final location.

Kvittem et al. (2012) used a semi-submersible wind turbine similar to the WindFloat concept in the comparison of various hydrodynamic models. The Morison model is often used in aero-hydro-servo-elastic codes developed from the wind industry such as HAWC2, while the potential flow model with quadratic drag forces is commonly applied in time-domain global response analyses using the codes developed in the offshore oil and gas industry, such as Simo-Riflex-AeroDyn. The Morison model can provide a good representation of the motion responses, as compared to the potential flow model, if proper added mass coefficients are selected and stretching of wave kinematics and dynamic pressure under the columns are considered.

Wind turbine design typically involves a significant number of coupled dynamic analyses in the time domain, and one important aspect of these is to directly obtain the responses in the floater members. Luan et al. (2013) developed a modelling method that can be used in the time domain to obtain the loads in the braces of a semi-submersible wind turbine structure. The semi-submersible floater model consists of columns as rigid bodies, with hydrodynamic loads calculated based on the potential theory, and braces connecting columns as beam elements with the Morison-type loads. A case study of the ULS design check for the brace system of the OC4 semi-submersible wind turbine was performed to illustrate the developed method.

3.2.3.2 Global response analysis

Floating wind turbines differ from bottom-fixed turbines by their larger rigid-body motions, the importance of the coupling effects between wind and wave loads and induced responses, and increased challenges regarding the automatic control system. These complexities require coupled tools for dynamic analysis, which also take into account the control actions. In the last decade, various floating wind turbine concepts have been proposed and developed. Different types of floaters represent different dynamic behaviours in wind and waves, and therefore lead to different responses in the rotor, tower and wind turbine drivetrain. Comparative studies on the dynamic behaviour of spar, semi-submersible and TLP floating wind turbines have been conducted for both operational and survival conditions.

Jonkman and Matha (2011) compared three floating concepts (spar, TLP and barge), supporting the NREL 5MW wind turbine. Dynamic responses under combined wind and wave loads were predicted by coupled analysis using FAST. Wind turbine aerodynamics were modelled by blade element momentum theory, and linear hydrodynamics and mooring spring models were also considered in the analysis. The three concepts were compared based on the calculated ultimate loads, fatigue loads and instabilities. The barge concept led to the highest load in the turbine, while the differences in the loads between the spar and TLP concepts were not significant; except for the loads in the tower, which were greater in the spar system.

Bagbanci et al. (2011a) studied the dynamic responses of a 5MW, spar-type, floating wind turbine. A hydrodynamic study of the floater was performed and the added mass, damping coefficients and excitation forces from linear potential theory and the hydrostatic data were obtained. Using the hydrodynamic data, the aero-servo-hydro-elastic simulation for the spar-type floating wind turbine was carried out. Further, a brief comparison of spar-type and barge-type offshore floating wind turbines was performed by Bagbanci et al. (2011b) with simulation results for tower base motions and platform motions for various wind conditions being obtained. It was observed that with the increase in wind speed the pitch motion of the spar type floating wind turbine increased, whereas the pitch motion decreased for the barge type floating wind turbine.

Roald et al. (2013) studied the effect of second-order hydrodynamic loads on a spar and a TLP based wind turbine. Using the proposed method, the importance of the second-order effects was assessed for the OC3-Hywind spar and the UMaine TLP. The comparison showed that the second-order forces were very small for the OC3-Hywind spar.

Sweetman and Wang (2012) presented the theoretical developments underlying an efficient methodology to compute the large-angle rigid body rotations of a floating wind turbine in the time domain. The tower and Rotor-Nacelle Assembly (RNA) were considered as two rotational bodies in space, for which two sets of Euler angles were defined and used to develop two systems of Euler dynamic equations of motion.

Jeon et al. (2013) determined the dynamic response of a rigid cylindrical floating substructure moored by three catenary lines under long-crested irregular waves using a fluid-rigid body interaction simulation. A numerical investigation of the dynamic response of spar-type floating substructure due to wave excitation was performed. The upper part, composed of wind turbine blades, hub and nacelle, was simplified as a lumped mass, and a dynamic model of three catenary mooring lines was considered.

Bae and Kim (2014) assessed the global performance of a spar-type floating offshore wind turbine with two different extreme environmental conditions. The coupled analysis included time-varying aerodynamic loading and damping, tower-blade elastic deformation, blade-control-induced loading, and the gyroscopic effect of the rotating blades. A numerical prediction tool was developed for the fully coupled dynamic analysis of the system in the time domain including aero-loading, blade-rotor dynamics and control, mooring dynamics, and platform motions so that the influence of rotor-control dynamics on the hull-mooring performance could be evaluated.

Karimirad and Moan (2013) performed a stochastic analysis of a tension-leg spar wind turbine subjected to wind and wave actions and the dynamic motions, structural responses, power production and tension leg responses were obtained. The negative damping, rotor and tower shadow effects were discussed when studying the power performance and structural integrity of the system.

Apart from the code-to-code comparison of different numerical tools (as discussed in Section 3.2.1), validation against model test results or field measurements is an important step for developing such numerical tools. Publically available field measurements are limited and the code-to-experiment validation in the current stage focuses on the use of results from various laboratory tests, see Section 3.3.1.

Utsunomiya et al. (2013) developed an analysis tool to assess the dynamic response of floating offshore wind turbines under extreme environmental conditions. The dynamic analysis tool consists of a multi-body dynamics solver, considering aerodynamic loads, hydrodynamic loads and mooring loads. Detailed comparison with the experimental results of a small size (100 kW) spar wind turbine at sea were performed in order to validate the model; where the wind, current and wave actions were applied simultaneously.

Coulling et al. (2013) compared FAST predictions with MARIN test data for a semi-submersible floating wind turbine at 1:50 scale. The focus of the comparison were system global and structural responses resulting from aerodynamic and hydrodynamic loads. The comparisons indicated that FAST captures many of the pertinent physics in the coupled floating wind turbine dynamics problem. The potential areas of improvement for the code FAST and for the experimental procedures to ensure accurate numerical predictions were also highlighted.

Gueydon and Weller (2013) studied floating foundations for wind turbines and subsequently developed a numerical model of a semisubmersible floater supporting a wind turbine. The model was calibrated against model test results, including static loading and decay tests, and the simulation results obtained were compared with the model test results for two sea states without wind: a white noise sea state and an operational sea state.

Philippe et al. (2013a) and Philippe et al. (2013b) performed a coupled dynamic analysis of a semi-submersible floating wind turbine and compared it with their model test results. Hydrodynamic loads were calculated using a linear frequency domain approach. In addition to the hydrodynamic damping and hydrostatic restoring effects, the aerodynamic damping and gyroscopic stiffness were also considered. The numerical analysis results agree well with the model test results when comparing the motion Response Amplitude Operators (RAOs) in waves.

Suzuki et al. (2013) developed an analysis code, UTWind, for the assessment of rotor-floater-mooring coupled response. In UTWind, blades and floater are modelled as frame structures using beam elements, while mooring lines are modelled as lumped masses. The numerical results by UTWind were compared with experimental results in wave and wind-wave coexisting conditions with/without blade pitch control. A good agreement was obtained for these cases. The code also reproduced the response due to negative damping discussed at design stage.

3.2.3.3 Design and analysis of wind turbine components

The drivetrain in a wind turbine converts mechanical energy from the rotor shaft to electricity via a generator, and it is an integral part of a wind turbine system. Traditionally, high-speed gearboxes were dominant drivetrain systems for wind turbines, with a market share above 85% (Kaldellis and Zafirakis, 2012). However, along with the development of offshore wind technology, a wide range of options of the drivetrain technologies are now available, including medium-speed (hybrid) gearboxes, direct drives, hydraulic drives, differential, multiple shaft and variable speed gearboxes.

Performance of a mechanical/hydraulic drivetrain must be tested at full scale (not at model scale) using a test bench in a laboratory. In this manner the global loads on drivetrain shaft can be imposed more accurately based on the knowledge regarding global behaviour of the whole wind turbine, or alternatively from field testing of wind turbines (Oyague et al. (2009), Link et al. (2011), Helsen et al. (2011a)). The high-speed gearbox developed by NREL–known as GRC (Gearbox Reliability Collaborative) 750kW–has been used in many studies (Xing et al. (2013), Guo et al. (2014)). This drivetrain is of a high-speed generator, one-stage planetary, two-stage parallel and three-point support type.

With the wind industry moving offshore into deeper waters, the drivetrains must be properly designed with due consideration of various load effects in order to increase reliability and avoid costly offshore repairs. Similar to that of a wind turbine system, a consistent approach should be applied, considering all the phases of the drivetrain life cycle, i.e. design, manufacturing, operation and monitoring, fault detections, life extension and decommissioning.

The current design approach for wind turbine gearboxes is based on the IEC 61400-4 guideline (IEC, 2012) which refers to ISO 6336 series of standards (ISO, 2006) for gear components used in alternative industries. In these design codes, gears are designed using a semi-probabilistic approach incorporating safety factors or “application factors”. Wind turbines experience significant dynamic loads due to wind turbulence, rational rotor excitations and turbine control. These also lead to dynamic responses in the drivetrain system. A design approach based on direct calculation of load effects is preferable. The eigen-frequencies of a gearbox (except that of the first torsional mode) are much higher than the wind turbine excitation frequencies, therefore a decoupled analysis method can be successfully applied (Xing and Moan, 2013). In such method, the main shaft loads are obtained from a global analysis model with a simplified 1-DOF (torsional) drivetrain model and then applied as input to a detailed MBS (multibody simulation) or FE (finite element) drivetrain model (Peeters et al. (2006), Helsen et al. (2011b), Xing and Moan (2013)), together with the drivetrain accelerations to represent the inertial loads.

Nejad et al. (2013) performed a long-term extreme value analysis of gear-transmitted loads due to the main shaft torque with multibody simulations, and a simplified method was demonstrated for the gear transmitted load calculation. The long-term extreme value of the gear transmitted loads for wind speeds from the cut-in to the cut-out values was calculated and three statistical methods for long-term extreme value analysis of the main shaft torque in the offshore wind turbines were presented.

Floating wind turbines may increase dynamic responses in the drivetrain due to motions excited not only by wind loads but also by wave loads. Xing et al. (2013) studied the dynamics of the 750kW GRC drivetrain on a spar floating wind turbine. Global aero-hydro-elastic-servo time-domain analyses were performed using HAWC2, while the commercial code SIMPACK was used to carry out multi-body drivetrain time-domain analyses. The comparison between a spar-type floating wind turbine and an equivalent land-based turbine indicated that in general there are increases in the standard deviations of the internal drivetrain responses (such as the tooth contact forces, bearing loads and gear deflections) in the floating device. These changes are a result of increased main shaft loads in the floating wind turbine, especially the non-torque loads.

3.2.3.4 Mooring analysis and design

Offshore wind turbines in deeper waters are exposed to stronger and steadier winds which can be used to improve overall efficiency of the wind farm. However, in water depths greater than 50m fixed support structures are not a cost-effective solution. During development of such wind farms, existing mooring technology and numerical models from the offshore oil and gas industry may be applied.

Comparison of an uncoupled and a coupled approach for estimation of semi-submersible FWT response was achieved by Masciola et al. (2013). In the study, the uncoupled model was formed using FAST while the coupled model was enabled by linking FAST to OrcaFlex. A key finding of the study was that the mooring line dynamics had a limited role on the influence of surge and heave motions, but are significant when observing the tensions in the mooring lines in extreme sea states. The authors also noted that in the case of a snatch load, there are large differences in the estimation of platform responses between the two models. Masciola and Jonkman (2014) implemented a dynamic mooring line model into the open-source Mooring Analysis Program (MAP) for use in the FAST modularisation framework. The lumped mass model was selected with consideration of external forces due to hydrodynamic loading, gravity and seabed contact.

Hall et al. (2014a) evaluated mooring line model fidelity for the OC3-Hywind, the ITI Energy Barge and the NREL TLP type offshore floating wind turbines. The three standard floating wind turbine designs were implemented and tested using a set of steady and stochastic wind and wave conditions.

An increased probability of slack line events is a particular problem within the design of FWTs (Hsu et al., 2014). These events usually occur due to a combination of low pre-tensions, lightweight platforms, shallow water depths and large platform motions in response to a survival storm condition. However, such events have the potential to occur in various sea states, and are not necessarily limited to extreme conditions. Hsu et al. (2014) used available model test data for a semi-submersible wind turbine to investigate how snatch force of the mooring lines may influence the motion and vice versa. There was a reasonably strong correlation between the tension spikes and wave-induced motion, as well as the vertical motion of the fairlead. Robertson et al. (2013) noticed that several slack-line events occurred for wave-only and combined wind/wave cases with large wave heights, during the tests of a TLP FWT. Each of the events was caused by the passing of a large wave that caused the tension in one of tendons to go negative–i.e. the tendon was in compression. The presence of these events, however, merely indicates that this TLP design was not sufficiently robust.

A parametric study of the dynamic response of spar-type wind turbine with three catenary mooring lines in irregular waves was undertaken by Jeon et al. (2013). Through numerical experiments, the time and frequency domain responses were investigated with respect to the total length and connection position of mooring lines. It was found that the surge and pitch motions were minimised when the three catenary lines were connected at the centre of buoyancy or slightly above the centre of buoyancy.

Fylling and Berthelsen (2011) presented a program for conceptual optimisation of FWT's support structure of the spar buoy type, including the mooring system and power cable. In their approach, the optimisation variables were spar buoy shape, height and diameter of column sections, mooring line and power cable data and vertical position of mooring line fairleads. A nonlinear optimisation approach with arbitrary constraints was used where the objective function was the spar buoy, mooring line and power cable costs. A mooring system optimisation procedure for FWTs using frequency domain analysis was proposed by Brommundt et al. (2012). The work emphasised the cost reduction of catenary mooring systems for the semi-submersible wind turbine type. Benassai et al. (2014) conducted a similar study focused on minimising the catenary mooring system weight of a FWT with a tri-floater, semi-submersible support structure, with reference to ultimate and accidental loads.

Two main lines of research are apparent in recent studies with respect to mooring system for FWTs. The first focused on development and validation of mooring system numerical models within the model of FWT response. In general, development started from implementation of quasi-static models taking into account only non-linear restoring forces of the mooring system. Subsequently, more sophisticated models capable of describing dynamics of mooring lines have been developed based on experience from the oil and gas industry. Within this line of research special attention has been given to slack line events of mooring systems. The second line of research considers optimisation of the design process of the FWT in order to reduce the cost of mooring systems.

3.2.3.5 Challenges for design and analysis of floating wind turbines

Refined versus simplified analysis methods
The majority of the coupled tools for analysis of floating wind turbines, discussed in the previous sections, are applied in time domain in order to capture nonlinear effects from aerodynamic or hydrodynamic loads, nonlinear geometrical effects due to large motions, and automatic control. Further development and validation of these numerical tools should be considered in the future.

However, it is also interesting to develop simplified methods which are more useful at a preliminary design stage, in view of a large number of simulations needed for long-term response analysis for ultimate and fatigue design check, or for design optimisation.

Karmakar and Guedes Soares (2013) performed dynamic analysis using the environmental contour method to estimate the long-term extreme loads for semi-submersible offshore floating wind turbine.

For fatigue limit state design, efficient and accurate analysis methods are required. Kvittem and Moan (2015) compared the frequency domain models for the tower base bending moment with fully coupled, nonlinear, time domain simulations. The predictions from this model agreed reasonably well with the results from a fully coupled, nonlinear analysis in Simo-Riflex-AeroDyn, and it was assumed that bending moments in the tower base were primarily caused by platform motions, accelerations and rotor forces, and that fluctuations in the axial force were negligible.

Using the basis function approach Hall et al. (2014b) studied the optimisation of a FWT using a hydrodynamics-based method. A frequency-domain model was used to evaluate the design space, applying linear hydrodynamics for the floating platform and linearized representations of the wind turbine and mooring system. Optimisations were run to find the platform design that minimised nacelle accelerations for two different mooring systems, and reasonable results were obtained.

Behaviour of floating wind turbines under fault conditions
Modern large-scale wind turbines typically have variable-speed, pitch-regulated, upwind rotors. The controller is designed and implemented to maximise the power extraction efficiency for below-rated wind speeds via generator torque control, and to mitigate loads and achieve constant power output for above-rated wind speeds via blade pitch control (normally collective control of the three blades). Faults, or failures, in wind turbine components (both hardware and software) may lead to less power production and increased dynamic loads in the system. Although IEC 61400-1 (IEC, 2005) and 61400-3 (IEC, 2009) define design load cases involving wind turbine faults, no detailed procedures for modelling and analysis of faults, and the subsequent system responses, are specified.

Faults do, however, occur in wind turbine systems. The EU ReliaWind project analysed the long-term operational data and fault records of 350 onshore wind turbines (Wilkinson and Hendriks, 2011) and presented a reliability profile for wind turbine components. Among all of the components, the blade pitching system has the highest failure rate. Pitch controller faults may reduce power production and increase dynamic loads. Pitch actuator faults have the potential to cause a blade to be stuck at a certain pitch angle and may increase the aerodynamic loads on that blade. For floating wind turbines, excessive motions can be excited by the unbalanced aerodynamic loads on the rotor plane due to pitch actuator faults (Johnson and Fleming (2011), Jiang et al. (2013)). This also increases the loads on the drivetrain of a floating system, as the bending moments on the main shaft are strongly affected (Xing et al., 2013). For emergency shutdown, it is common practice to pitch all of the blades to feather simultaneously at a maximum pitch rate. The presence of pitch system faults will influence the effectiveness of emergency shutdown.

So far, there has been limited research carried out in this direction and future work on wind turbine faults is imperative. This may include physical understanding and numerical modelling of faults, assessment of the effects of faults on system responses, effective alleviation methods or procedures, condition monitoring for fault diagnosis and detection and fault-tolerant control.

Floating vertical axis wind turbines
Recently, there has been a resurgence in interest in vertical axis wind turbines (VAWTs) for offshore applications with floating foundations. The EU DeepWind project (http://www.deepwind.eu/The-DeepWind-Project) considers a novel spar-type vertical axis wind turbine, with focus on the development of tools for optimisation and design and the verification against model test results.

Wang et al. (2014) discussed the potential application of a VAWT on floating foundations. There are several advantages to the use of a VAWT: power generation is independent of wind direction, they have a low CoG for improved hydrodyanmic performance, and access to the drivetrain and generator is facilitated for improved maintenance and repair strategies. However, compared to an equivalent 5MW HAWT, the large yaw motions induced by the rotor torque impose challenges for design of the mooring system.

Borg et al. (2014a) developed a numerical model for VAWT analysis. Aerodynamic theories suitable for VAWTs were discussed. Borg et al. (2014b) focused on modelling of mooring systems and structural behaviour of floating VAWTs, discussing various mathematical models and their suitability within the context of developing a model of coupled dynamics. The advantages and downfalls of each model were noted, from the simple force-displacement relation to the nonlinear finite element model.

VAWT development thus far is limited when compared to that regarding HAWTs. Several directions might be considered in the future work: further development and validation of numerical tools, development of an advanced control strategy to reduce power variation and dynamic loads, development of safe procedures for start-up and shutdown and novel floater and mooring design to reduce system motions, in particular yaw motions.

3.3 Physical testing

Laboratory testing at small scale is an important part of conceptual study for novel concepts of offshore wind turbines. It enables detailed investigation of underlying aerodynamic and hydrodynamic phenomena. Field testing of large scale or prototype of offshore wind turbines is also a crucial step to demonstrate both the technological and economic feasibility for further development towards a full commercialisation.

Both laboratory and field tests are very valuable for validation of numerical tools if the measurements of both environmental conditions and system responses are properly performed. Laboratory testing has the advantage of being well-controlled and having repeatable environmental conditions. For example, extreme wind and wave design conditions can be re-produced in the lab, but they might not occur at sea within a limited amount of testing time. However, the generation of wind fields with good quality in open space (for example in a wave tank) is difficult. The scaling effect introduces another uncertainty to interpret the laboratory test results. For an offshore wind turbine, it is important to scale both the aerodynamic loads according to Reynold's law and the hydrodynamic loads using Froude's law. However, it is not possible to simultaneously satisfy both scaling laws (Müller et al., 2014). For prototype tests at full scale, there is no scaling problem, but the measurements of both wind and wave fields in particular might not be accurate and sufficient for validation of numerical tools. Low long-term reliability of the instrumentations might be another problem for testing at sea. For drivetrains and generators, full-scale tests are preferred.

3.3.1 Laboratory testing

Recent laboratory tests of offshore wind turbines are primarily concerned with floating concepts: spar, semi-submersible and TLP. While model tests of bottom-fixed offshore wind turbines focused on nonlinear wave loads on support structures in extreme wave conditions.

In order to study the dynamic responses of a monopile wind turbine under breaking wave loads, a model tests using a representative 1:30 wind turbine tower and monopile with realistic flexibility was performed in MARIN's Shallow Water Basin (De Ridder et al., 2011). The water depth was 30m and the diameters of the tower and the monopile were 5.4 m and 6m at full scale, respectively. The 1^{st} and 2^{nd} bending modes were correctly modelled by adjusting the distribution of bending stiffness and weight along the tower height. The test involving a focused breaking wave revealed that the horizontal acceleration at nacelle height can reach up to 0.9g ($g = 9.81\ m/s^2$). This implies significant loads on the wind turbine components, such as the drivetrain.

As part of the Danish 'Wave Loads Project', model tests of a flexible pipe in steep and breaking waves were performed. The 1:36.6 test pipe represented the NREL 5MW monopile with a diameter of 6m at full scale in a water depth of 20m. The test results were used to validate three numerical methods (Paulsen et al., 2013), a linear potential flow solver, a nonlinear solver and a CFD method (the Navier-Stokes/VOF solver). In general, the linear solver deviated significantly from the experiments for nonlinear steep waves. The nonlinear solver performed equally well as the CFD method for most of the cases, but for the near-breaking and breaking waves, the wave force is more accurately captured by the CFD method due the ability to handle wave breaking.

A summary of model tests on floating wind turbines was presented by Müller et al. (2014). In most of the model tests the floater was geometrically scaled, yet still modelled as one rigid body, while the flexibility of the tower was realised in some tests in order to capture the elastic response. Mooring lines were represented simply as springs, or as physical lines including the dynamic effect as well.

While model tests can be used to examine the uncertainties related to hydrodynamic and aerodynamic load prediction for isolated effect, the lack of consistent scaling laws make it difficult to investigate the effect of simultaneously acting wave and wind loads. Often very simple models of the aerodynamics have to be applied in the model tests (Coulling et al., 2013). There exist a variety of methods for modelling the rotor. A geometrically-scale rotor at model scale would produce less thrust force due to lower lift and higher drag coefficients as compared to the full-scale rotor (Fowler et al. (2013), Philippe et al. (2013a)). Therefore a re-design of the rotor might be necessary in order to achieve the corresponding thrust curve (Martin et al., 2012). Alternatively, the rotor may be modelled simply as a disk to reproduce the thrust force (Roddier et al., 2010), or a controlled fan providing active force in order to mimic the thrust force (Azcona et al., 2014).

Roddier et al. (2010) discussed the development of the WindFloat concept and highlighted the challenges for any offshore floating wind turbine foundations, related to turbine design considering floater induced motions, fabrication and installation procedures and costs. Model tests were performed in a wave tank facility, using fans and a drag disk placed on the model to generate wind loads and a rotating rotor behind the disk to model gyroscopic effect. The numerical hydrodynamic results were compared to the experimental measurements.

A series of model tests of three floating wind turbine concepts (spar, semi-submersible and TLP) at 1:50 scale were performed at MARIN through the DeepCwind project, see Figure 7. The main objective of this research project is to develop a proper scaling methodology, to realise a model wind turbine for laboratory testing and to validate numerical codes (Fowler et al. (2013), Martin et al. (2012), Robertson et al. (2013)). Robertson et al. (2013) summarized the results and the experiences obtained from the first phase of the tests as well as the comparison against the numerical code FAST. It was found that using geometrically scaled rotor blades produced too low thrust force which is of significant importance for pitch motion of the floating wind turbines, and therefore increased wind speeds need to be considered in order to achieve the target thrust force. The comparison between the FAST simulations and the test results showed a good agreement in general, but also revealed the importance to include a second-order hydrodynamic model as well as a dynamic mooring line model in FAST. The same approach was used in the test of a semi-submersible with brace systems in the Hydrodynamics and Ocean Engineering Tank at ECN (Philippe et al., 2013a).

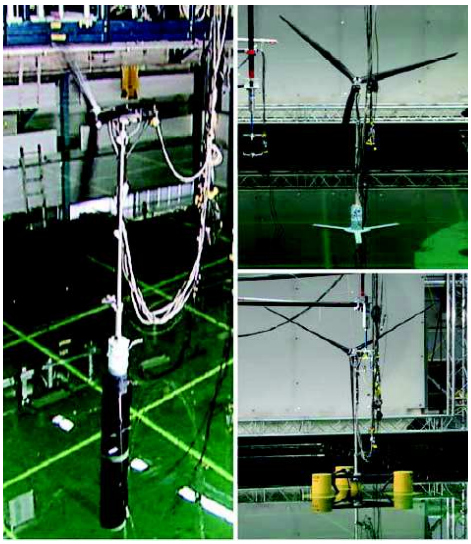

Figure 7. The three floating wind turbine concepts tested at MARIN (left: spar; right-top: TLP; right-bottom: semi-submersible) (Robertson et al., 2013).

In order to overcome the problems related to a geometrically scaled rotor, a 'performance-matched' wind turbine model with re-designed blade geometry was developed at University of Maine (Martin et al., 2012) and built in 2013 at MARIN (De Ridder et al., 2014). The new turbine model can produce the target thrust coefficients of the NREL 5MW wind turbine at model scale for Froude-scaled wind speed. Together with an active pitch control mechanism and a new high-quality wind generator setup, this turbine was then used in the additional tests of the DeepCwind semi-submersible wind turbine (Goupee et al., 2014) and in the tests of the GustoMSC Tri-Floater at MARIN (Huijs et al., 2014).

Model tests of floating wind turbines have also been performed at other facilities with focus on hydrodynamic behaviour. Several tests have been conducted considering different designs of spar-type hull (Shin et al. (2013), Sethuraman and Venugopal (2013)). A 1:100 semi-submersible with a single-point mooring system was tested at the Ocean Basin of Institute of Industry Science, at the University of Tokyo. Model tests of a TLB for offshore wind application were conducted by Myhr et al. (2011). Wehmeyer et al. (2013) performed a model test at 1:80 scale for a tension leg moored floater as support of a floating wind turbine in the 3D deep water basin of the Hydraulics and Coastal Engineering Laboratory at the University of Aalborg. The test focused on the ULS behaviour and it was shown that the inclusion of high-order hydrodynamics was essential, especially regarding TLP-specific responses such as ringing and slack line events. Calibration of a scaled finite element model by comparing the scaled natural periods of a measured TLP system show that the hydrodynamic added mass coefficients for complex structures are in contrast to the literature as per Adam et al. (2013) and accepted design codes (e.g. DNV-GL). This was traced back to a semi-transparent characteristic of the structure.

In addition, hybrid model testing has been undertaken in order to try and avoid the scaling problem, in which either aerodynamic loads (Hall et al., 2014c) or hydrodynamic loads (Bottasso et al. (2014), Bayati et al. (2014)) are calculated by numerical codes and reproduced by real-time controlled actuators. However, such testing technique relies strongly on the accuracy of the applied numerical codes and the response characteristic of the actuators. Further validation of such methods needs to be conducted.

3.3.2 Field testing

There exist several intermediate-scale floating wind turbines which are currently under test at sea. Such tests are usually developed with the aim of gathering information for the development of large full-scale floating turbines. The 100kW downwind spar floating wind turbine was launched in June 2012 near Kabashima Island, Japan. Since then, the test turbine has been attacked by several severe typhoons and it survived with no damage. The study by Utsunomiya et al. (2013) and Ishida et al. (2013) also showed a good agreement between the numerical simulations and the field measurements for motion and structural responses of the spar wind turbine in extreme wind and wave conditions.

A 1:8 scale prototype of a 6MW, semi-submersible, floating wind turbine (VolturnUS) was deployed off the shoreline of Castine, Maine, USA in June 2013. The turbine has a rated power of 12kW. Comparison of the measurement data with numerical results using FAST shows that the numerical code is suitable for modelling a nearly full-scale floating wind turbine in both operational and extreme design environments (Viselli et al., 2014).

There are two full scale, floating wind turbine prototypes that are currently being tested at sea; the 2.3MW Hywind deployed in 2009 and the 2MW WindFloat deployed in 2011. These two prototypes have gone through several years of testing, and have demonstrated the feasibility of floating wind turbine technology. In particular, the power performance of these two floating turbines are in excess of expectations (Nielsen (2013), Maciel (2012)).

The capacity factor of Hywind was in the order of 44–54% for the northern North Sea conditions (Nielsen, 2013), much higher than 30-35% of typical offshore bottom-fixed wind turbines in the North Sea. In addition, comparison with the measured data has shown the capability of numerical tools to capture structural responses of the Hywind with a reasonable level of accuracy. The next step for Hywind developer, Statoil, is to optimise the floater to support larger turbines in order to achieve a cost-effective solution for a small farm of floating wind turbines.

However, there is no detailed technological information publically available regarding these projects as they have been developed by industrial companies as opposed to research establishments. There is therefore a need to develop research infrastructures for testing of full-scale wind turbines through which the community at large can have full access to the measurement data in order for development of the industry to progress.

3.4 Transportation, installation, operation and maintenance

Transportation, installation, operation and maintenance of offshore wind turbines has become an important part of the economics associated with offshore wind farms. The key for cost reduction is to increase the efficiency and the workability of relevant vessels that are involved in these phases; however, in general, there exists limited research work published in this area. The focus in this section of the report is relating to transportation and installation of offshore wind turbine components (foundation, tower, nacelle and blades). Currently, installation of these components (individually or in a pre-assembled manner) is carried out primarily using large jack-up vessels, or in some cases floating, heavy lift, DP (Dynamic Positioning) installation vessels. New transportation and installation methods and vessels have been proposed recently. It should be mentioned that wind turbine operation and maintenance are not covered by this report. These aspects are discussed in detail in Rademakers et al. (2011).

3.4.1 Current industry and research development

New transportation and installation vessels, methods and concepts

Kim et al. (2012b) described a jack-up wind turbine installation vessel as the world's first vessel which was a self-propelled and self-elevating platform. The vessel was designed to carry out lifting operations using cranes onboard in jacked-up mode for water depths of up to 45 m, and also serve as transportation and storage unit carrying wind farm structures and consumables.

Norwind Installer and Ulstein (Østvik, 2012) have designed a new installation vessel incorporating a DP system. The DP vessel is designed for world-wide operations with a focus on pre-piling and jacket/tripod/transition piece installation for the offshore wind industry in North Europe. The vessel was designed for maximum efficiency and cost effectiveness, and features an 800ton heave compensated offshore crane on the starboard side, while a pre-piling template can be located on a support structure at the stern. The vessel can carry 4 jackets each trip, or alternatively at least 24 piles or up to 12 transition pieces on the large open aft deck.

Saipem SA proposed a new offshore wind turbine installation device Castoro Vento vessel (Ruer et al., 2009). The vessel is based on the float-over technology which has been used in the offshore oil and gas industry. The vessel is a U-shaped barge equipped with several ballast water compartments to allow ballasting/de-ballasting operations. It is designed to transport wind turbines up to 6MW, for installation in water depths between 25–35 m. The vessel can carry a fully assembled turbine including the foundation (gravity-based, steel tripods and jacket structures) to the offshore site and then install it on a pre-prepared seabed utilising ballasting operations. Therefore, no offshore lifting operations are needed.

The Merlin concept (Bland, 2004) was proposed to install fully-assembled wind turbines offshore. The complete turbine is intended to be lifted out onto a bespoke installation barge for transportation to the offshore site where it is rotated to the vertical position and connected to a preinstalled foundation in a single operation. The analysis results showed that the Merlin system could operate in higher sea states than most conventional turbine installation vessels.

The Dutch company Ulstein Sea of Solutions and SPARCS have developed a new wind turbine concept, called F2F (floating to fixed), aiming to reduce the high offshore installation costs associated with the offshore wind industry (Ulstein, 2012). The concept is constructed, pre-assembled and commissioned onshore, then floated to a stable working draft and towed to the offshore location. When arriving at the location, it is lowered to the sea bed through a ballasting system and fixed in place by suction anchors. When maintenance and repair is required, it can be re-floated again and subsequently towed to shore.

Reinertsen AS have proposed a novel concept of a self-installing offshore wind turbine with gravity-based foundation (Wåsjø et al., 2013). The concept combines installation of the substructure and turbine in one single operation by using two structurally connected standard barges. A cost saving potential in the early phase of 17% was identified compared to a steel jacket solution.

From the concepts described above, it can be seen that there is a tendency to develop new vessels/methods which facilitate the installation of fully-assembled wind turbines thereby avoiding risky and weather-sensitive offshore lifting operations. However, the studies on these new concepts are at a very early stage of development, and more effort into detailed design and analysis should be performed in order to prove the feasibilities of the different concepts.

Transportation and installation of floating wind turbines

Up to now, only a few wind turbines in the world exist that are supported on a floating support structure. The installation methods for floating wind turbines are quite different from those for bottom-fixed wind turbines due to increased water depths. For turbine installation in shallow water, jack-up vessels are normally used to provide stable platform for lifting and offshore bolting, which could hardly be carried out by a floating vessel with motions in six degrees of freedom. However, for deep waters, if onshore assembly is chosen, the installation can only be performed by floating vessels, which is in itself challenging and costly. In order to reduce installation costs and to make floating wind turbines more cost-effective, innovative installation strategies are required.

The Hywind demo (Statoil, 2014) has draft of 100 meters and installation of the turbines on top of the spar in shallow waters is not possible. Therefore, the spar hull was wet-towed horizontally to a near shore fjord, where it was temporarily moored and then upended through ballasting. An offshore heavy lift vessel was subsequently used to transport and assemble the turbine components. The fully-assembled wind turbine was then towed by three vessels to the offshore site, where it was connected to the pre-installed mooring lines.

The WindFloat prototype (PrinciplePower, 2014) was the first offshore floating wind turbine that was deployed without the use of any offshore heavy lift vessel. Due to the low draft of the semi-submersible, the complete structure was fully assembled onshore prior to being towed offshore. Once at the offshore site, a conventional catenary mooring system was connected to the floating wind turbine.

WindFlip is a specialized barge for transporting and installing spar type floating wind turbines (WindFlip, 2013). One fully-assembled turbine, lying in a nearly horizontal position on top of the deck of the barge is transported at a time. After the barge has been towed to the offshore site, it is slowly ballasted down, and the barge with the attached turbine flips 90^o until both are in the vertical position. The design of the barge is optimised to maintain stability throughout all phases of the flipping process. The turbine is then connected to a pre-installed mooring system.

For TLP wind turbines, the key challenges are related to the installation of anchors and tendons, as well as towing of the TLP floater itself.

3.4.2 Numerical simulations of marine operations

For validation and improvement of any installation method, careful numerical and experimental studies are important. Numerical simulation may help to identify critical phases of different marine operations, prior to the execution of these operations at sea. It will also provide a better basis to establish rational limiting criteria for safe operation, and to evaluate operational weather windows and associated probability of success. In a broader sense, numerical simulations in combination with weather forecasting could also be useful for decision-making in actual operations at sea. A variety of marine operations might be studied by numerical models. The focuses here are sea transportation analysis, lifting operation and docking operation of service vessels.

Donaire (2009) presented a program to perform the sea transportation analyses for a given barge and wind turbine configuration, which includes two modules: the sea keeping model of the barge and the sea transportation model considering wind turbine aero-elastic responses. The criterion to check the performance of the transportation was chosen as the acceleration limitation at the turbine nacelle, from which the limiting weather condition can be determined.

Graczyk and Sandvik (2012) performed a numerical study of lift-off and landing operations for wind turbine components on a ship deck using a frequency-domain approach for ship motion analysis. Two different vessels (one large supply monohull vessel and one small catamaran vessel) were considered in the comparative study. A limiting acceleration of the lift object was defined and used in combination with the probability distribution of sea states to determine the weather window for such operations.

Wu (2014) performed numerical analyses of docking operations between service vessel and offshore wind turbine for personnel and equipment transfer also using a frequency-domain method. In one case, a medium-size service vessel with motion compensation devices was considered. The limiting criteria for operability analysis of docking operation were defined as the compensation limits of the 6 degrees-of-freedom relative motions, velocities and accelerations between the docking device and the offshore wind turbine. In the second case, a small service vessel with a simple fender was considered. The limiting criteria were defined as no slip between the service vessel and the wind turbine tower at the touch point, which implies that the vertical force should be smaller than the friction force. The proposed frequency-domain approach was shown to be much more efficient than a time-domain method for the analysis of long-term operability.

Li et al. (2014) performed a detailed numerical study on the crane operation for lowering the monopile and jacket substructures through the wave splash zone to the sea bed using a floating installation vessel. Transient time-domain analyses of the coupled system of the installation vessel and the lift object were carried out considering the submergence-dependent hydrodynamic loads on the substructure. In particular, the vessel shielding effect (that is the reduction of the wave kinematics on the leeward side of the vessel) was studied and found to have a significant effect, depending on the vessel heading angle, on the dynamic responses of the substructure motions and lift wire tension.

Sarkar and Gudmestad (2011) and Sarkar and Gudmestad (2012) proposed a novel method to install monopiles by isolating the installation operation from the motion of the floating vessel using a pre-installed submerged support structure. A new substructure was designed to support the monopile against waves and currents during the initial phase of driving into the seabed. A simplified numerical model in Riflex was established to study the responses of the structures during the driving operation. The analysis results indicated the submerged support structure probably can increase installation weather window as compared to the existing installation technology.

3.4.3 Guidelines on marine operations for offshore wind turbine transportation, installation, operation and maintenance

There are no specific design rules or guidelines regarding marine operations for offshore wind turbine transportation, installation, operation and maintenance. The rules and guidelines established in the offshore oil and gas industry are often utilised, since they are also applicable to similar operations in the offshore wind industry. The objective of these guidelines is to provide methods and simplified formulations for establishing design loads to be applied for planning and execution of marine operations.

DNV Recommended Practice H301 (DNV, 2010) gives guidance on modelling and analysis of marine operations, in particular for lifting and towing operations. The GL Noble Denton Technical Guidelines and Rules also cover many marine operations, including load-outs, marine transportations (GL-NobleDenton, 2013a), marine lifting operations (GL-NobleDenton, 2013b), installation of concrete offshore gravity structures (GL-NobleDenton, 2013c) and jacket structures (GL-NobleDenton, 2013d). The NORSOK Standard J-003 (NORSOK, 1997) defines the basic requirements for vessels performing marine operations and for the planning, execution and work associated with such operations on the Norwegian Continental Shelf.

3.5 Rules and standards

Current standards or technical specifications for design of offshore wind turbines and their sub- structures essentially consist of the following documents for bottom-fixed wind turbines:

- IEC 61400-3 (IEC, 2009);
- DNV-OS-J101 (DNV, 2013a);
- GL (IV Part 2) (GL, 2005);
- ABS #176 (ABS, 2013a);

and for floating wind turbines:

- DNV-OS-J103 (DNV, 2013b);
- ABS #195 (ABS, 2013b);
- BV NI 572 (BV, 2010);
- ClassNK Guideline (ClassNK, 2012);

Although there exist design standards for floating wind turbines, the industry is still in an early stage of development, therefore further development and revision of these standards is necessary when the relevant industry experience is available.

A recent assessment of standards has been provided by the NREL (Sirnivas et al., 2014) which, although more focussed on US applications, includes review of institute standards API, IEC and ISO and class society guidelines published by ABS, BV, DNV and GL. These standards and guidelines are continually being assessed and updated (Karimirad (2014), Negro et al. (2014), Perveen et al. (2014), Woebbeking and Argyriadis (2013)).

The most common rules to certify offshore wind turbines are the IEC 61400-3 rule and the DNV-GL guidelines. The current edition of the IEC 61400-3 rule considers bottom-fixed offshore wind turbines. IEC has established a Technical Committee (TC) 88, developing the design rule for floating wind turbines. The guideline for floating sub-structures, however, is not yet published; a technical specification of IEC 61400-3-2 will be published in the near future.

The DNV-OS-J101 rule deals with offshore wind turbines with fixed substructures (monopiles and jackets). The DNV-OS-J103 rule regards to wind turbines with floating substructures. Similar to the DNV-OS-J101 standard, the GL (IV Part 2) handles with offshore wind turbines for fixed sub-structures. After the merge of DNV and GL in December 2013, all of the rules will be compiled and subsequently re-written.

Most of the other standards, both national and international, have been developed in line with IEC 61400-1 (IEC, 2005) and 61400-3. For example, ABS #176, also an international standard, issued first in 2010 and revised in 2013. It is mostly aligned with IEC 61400-3.

ClassNK (2012) published "Guideline for Floating Offshore Wind Turbine Structures" in July 2012. It applies to unmanned floating structures with a 20-year design life or over and to the tower and RNA as options. The guideline was developed referring to IEC 61400-1 and IEC 61400-3 and the related ClassNK Rules for the Survey and Construction of Steel Ships. The design principle implied in the guideline is to maintain the structural integrity of floating structures throughout their design lifetime without the need for docking and repair, and to consider the absolute minimum of damage stability and one line breaking in order to prevent drifting.

4. WAVE ENERGY CONVERTERS

Wave energy conversion technology has a large potential to contribute to the world's renewable, emission-free energy supply. A recent comprehensive study by the Electric Power Research Institute (Jacobsen, 2011) concluded that the recoverable wave energy resource along the coastlines of the United States is in the order of 1,000TWh/yr, which represents nearly 1/3 of the total electricity currently used in that country. Similar potentials exist for many countries around the world. WEC technology is still relatively immature when compared to wind, water, solar and even tidal power extraction, and it thus faces significant hurdles to achieving economically competitive designs. This chapter will attempt to summarise the main commercial and research developments that have taken place since the last ISSC report in 2012 (ISSC, 2012).

In the past three years, the number of test centres, prototype and pre-prototype wave power installations has exploded world-wide so that they are now too numerous to list in this condensed report. However, the International Energy Agency has run a Technology Initiative called Ocean Energy Systems (IEA, 2014b) since 2001, and they maintain a website listing world-wide Ocean Energy installations including Wave, Tidal, Thermal Gradient, Salinity Gradient and combined installations. As of the end of 2013, there were 22 open-sea testing facilities around the world, 15 in Europe, 5 in North America, and 1 each in Asia and Oceania. The total installed and approved-for-installation wave energy power is listed at 1.5MW in North America, 76MW in Europe, 4MW in Asia and 43MW in Oceania.

The European Commission has established an industry trade association for ocean renewable energy with the name Ocean Energy Europe (OEE, 2014). They have published an "Industry Vision Paper" which calls for a dramatic expansion of ocean renewable energy over the next forty years culminating in up to 100GW of online wave energy by the year 2050. The group outlines a number of barriers to achieving this goal, but the EC has also established an Ocean Energy Forum run by European Energy Ministers and senior industry figures which is actively working to advance the industry on three critical fronts: technology; finance; and environment/consenting. These developments suggest the possibility of a dramatic expansion in the WEC industry over the next few decades.

Concepts and development status

In contrast to wind and tidal energy, wave energy extraction devices span a large range of different concepts with over a hundred different designs being proposed over the years, many of which are currently under active development. Different types of WEC concepts have been studied, including:

- Attenuator;
- Point absorber;
- Wave surge converter;
- Oscillating Water Column (OWC);
- Overtopping or Terminator;
- Cycloidal lifting surface or cycloidal turbine wave absorber;
- Submerged pressure differential;
- Other.

According to Falcão (2010), these devices can be classified into three main categories based on the working principle, namely oscillating water column, oscillating bodies and overtopping. Falcão (2010) also listed the projects that have reached the prototype stage, or at least have received extensive development efforts, Figure 8.

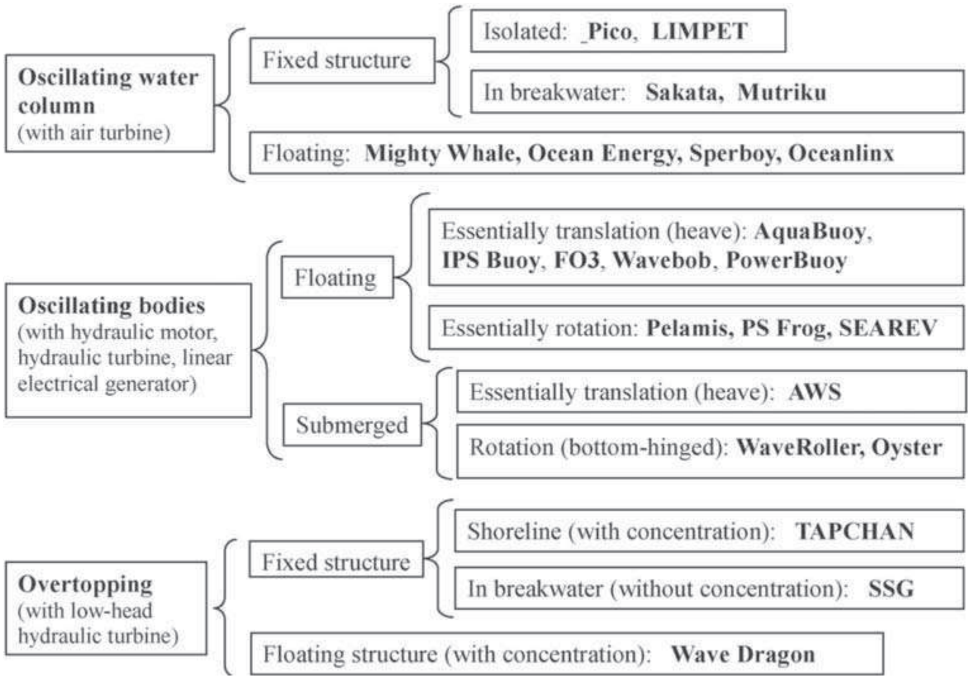

Figure 8. Wave energy technology classification (Falcão, 2010).

Despite this variety of concepts, the differences in scaled metrics, such as absorbed power per device volume or absorbed power per device surface area, are surprisingly small for a large number of designs (Babarit et al., 2012). One device, however, stands out in terms of the theoretically predicted absorbed power per device volume; the cycloidal lifting surface device originally invented by researchers at Delft University of Technology in the Netherlands (Hermans et al., 1990) and is currently being commercialized by Atargis Energy Corporation (Seigel, 2012). While predicting the ultimate COE for any WEC device is still rather uncertain, it seems clear that no radical breakthroughs have emerged over the past three years.

There has however, been much activity in this time. The FP7 project MariNet has allowed for a large number of ocean energy devices to be tested at the ever increasing network of European facilities. Several of these projects deal with wave energy, and they are listed on the webpage http://www.fp7-marinet.eu/access_user_projects_wave_energy.html. There are currently twenty-nine projects recorded here. The development stage of each project is also stated, using the convention:

1) Concept validation;
2) Design validation;
3) Sub-system validation;
4) Solo device validation;
5) Multi-device demonstration.

Only one of the concepts is at stage 5, two at stage 4 and the rest between stages 1 and 3.
The most critical topics of validation for these tests are:

- Power production in real sea conditions (scaled duration at 20-30 minutes) (11 tests);
- Mooring arrangement and its influence on the performance (9 tests);
- Initial estimates of the full system load regimes and accurate simulation of PTO characteristics (8 tests);
- Investigation of the physical processes governing the device response (some of which may not be well defined theoretically nor numerically solvable);
- Survival loading and extreme motion behaviour (7 tests).

Even though this collection is not exhaustive of the whole panorama worldwide, it gives a picture of the main topics of research and an idea of the current stage of development for WEC technology.

Although the technology is still rather young, a number of developers claim that their ultimate COE will be competitive with, or superior to, offshore wind energy once the mass-production stage has been reached. Verification of these claims will require continued, and ideally increased, research and government support for this emerging technology.

4.1 Numerical modelling and analysis

The general approach to the analysis of a WEC concept is to apply a sequence of increasingly more sophisticated models to capture more and more of the relevant physics, depending on the stage of development of the concept. Potential flow models are used in the initial stages, often starting with a purely theoretical model, followed by numerical calculations using a linear frequency-domain analysis and finally moving to a weakly-nonlinear time-domain formulation which can include the most important nonlinear effects from in particular the PTO and/or mooring system. These calculations are usually based on solutions using the Boundary Integral Equation Method (BIEM), as exemplified by the panel code WAMIT (Lee, 1995). In the case of simple geometries (e.g. vertical axisymmetric bodies), analytical solutions can be used as well (Mavrakos and Konispoliatis, 2012). This analysis is relatively fast and is suitable for refinement and optimisation of all aspects of the concept from the geometric shape to the mooring system and the PTO control strategy. Suitable models should also be included here for important viscous and possibly compressibility effects via empirical viscous damping coefficients and for OWCs air flow models for the turbine (see for example Conde and Gato (2008)). Recent examples of this analysis are reported by Rhinefrank et al. (2013) and Sheng et al. (2014).

In the later stages of design, fully nonlinear potential flow models and/or Euler or Navier-Stokes solvers (CFD) can be used to capture wave breaking and other highly nonlinear phenomena so as to perform ULS and survivability calculations. The computational effort for these more refined models is, however, very high and relatively few examples can be found in literature (Luo et al. (2014), Hu et al. (2011), Ashkan et al. (2013)). A recently completed Danish research project described at http://www.sdwed.civil.aau.dk/ collects a number of tools available for this purpose, with Li and Yu (2012) providing a description and an example of the basic analysis and design procedure.

Overtopping and bottom hinged devices are especially difficult to analyse, as they are generally strongly dependent on wave breaking and highly nonlinear motions which can undermine their survivability. For these devices, CFD solutions are normally required, but due to their prohibitive cost, it is important to first identify the critical conditions using potential flow to provide initial conditions for more comprehensive but more computationally expensive solvers.

4.1.1 Load and motion response analysis

Similar to the dynamic analysis of offshore wind turbines, the purpose of numerical modelling and analysis of a WEC, or an array of WECs, is to address on one hand the serviceability (power production) and on the other hand the safety (structural design with respect to ULS and FLS). Accurate numerical models are of great usefulness and importance to predict and maximize power production, to make acceptable and optimal component and structural design, and therefore to achieve reasonable economics of WECs. In this section, we reference and briefly discuss a number of recent publications collected into several broad focus areas.

Single device analysis

Li and Yu (2012) applies a full analysis procedure to a point absorber concept, running through all the stages of analysis.

Babarit et al. (2012) present a numerical benchmark study of eight generic WEC concepts, including seven oscillating bodies and one oscillating water column. In order to make a fair comparison of the devices, three performance measures of the annual power production per unit cost were adopted based on total mass, surface area and maximum PTO force. Time-domain numerical models were used for the analysis of global motions and power output, based on the linear frequency-domain hydrodynamic coefficients, but including the nonlinear effects from empirical viscous forces, PTO forces and end stops. Among the eight selected concepts, the bottom-fixed oscillating flap was found to be the most promising, though the differences in the total COE for the various devices was small.

Jeans et al. (2013) studied the performance of a 2D lift based cycloidal WEC (CycWEC) in unidirectional irregular, deep water waves, as a follow-up to their previous numerical and experimental work on the same concept in regular wave conditions. This concept consists of two hydrofoils attached by a cylindrical framework parallel to a horizontal main shaft. The structure is submerged close to the free surface and aligned parallel to the incoming wave crests. Potential flow theory is used, and each hydrofoil is modelled as a point vortex moving under a free surface. The hydrofoil position and bound circulation are controlled based on a feedback flow control using a sensor located up-wave of the device and wave state estimator, to achieve high efficiency for irregular waves. Their results show that the capture width ratios for incident wave fields consisting of 7 and 10 main regular wave components were 0.85 and 0.77, respectively. These results were validated by 1:300 scale experiments, which also measured a capture width ratio of 0.77 for similar irregular wave conditions.

Sakai et al. (2014) considered a Salter Duck-type device which uses a rotating internal pendulum as the PTO. Linear frequency-domain calculations predict that the device can achieve a capture width ratio between 0.75 and 1.

Lovas et al. (2010) used linear potential flow theory to evaluate the performance of a shore mounted, circular OWC at the tip of a coastal corner of any angle. A semi-analytic solution was obtained using eigen-function expansions, to give relatively simple solutions for the hydrodynamic and power performance. The energy extraction efficiency for a convex and a concave corner were compared to existing solutions for a thin breakwater and a straight coastline. The inherent advantage of the pneumatic system was explored to show that the column radius should not be too small to yield a broad bandwidth of high efficiency. In addition to the effects of system sizes, they have introduced a simpler strategy of optimisation by assuming that the parameter representing the PTO device can take two different values, one for the high-frequency range and one for the low-frequency range. This strategy was found to be comparable to the theoretically ideal strategy where the parameter can be controlled for any frequency.

Fonseca and Pessoa (2013) considered a floating OWC concept with a U-shaped chamber using a coupled model for the floater and the interior chamber motions. By tuning the natural periods of the roll motions and the interior chamber, they were able to obtain an average efficiency in irregular waves of 0.47. The average efficiency was defined as the ratio between the average air turbine power output and the average wave energy flux associated to a wave front with the width of the device (15m). The simplicity of this concept suggests that it could have a good COE.

Luo et al. (2014) presented an experimentally validated two-dimensional, fully nonlinear CFD model to analyse the efficiency of a fixed OWC device with a linear power take off system. In contrast to the linear wave case, for fully nonlinear waves, a substantial reduction of efficiency was observed with increasing wave height. Moreover, the optimal pneumatic damping coefficient was found to be dependent on the wave height. These results may lead to significant implications in the design and operation of practical OWC systems.

Gkikas and Athanassoulis (2014) developed a nonlinear system for identification of the pressure fluctuation inside the chamber of a 2D OWC device under regular wave excitation. A Wiener–Hammerstein cascade systemic scheme was assumed, which led to a truncated Volterra series representation of the functional analogue. The nonlinear thermodynamic equations were investigated for various combinations of excitation amplitudes and frequencies and it was found that the first three harmonics were the most significant when explaining the response of the OWC.

Single device optimisation

Kurniawan and Moan (2013) performed a geometric optimisation of submerged wave absorbers oscillating about a fixed horizontal axis, with the objective of minimizing two cost functions (i.e. the ratio of the submerged surface area to the maximum absorbed power, and the ratio of the maximum reaction force to the maximum absorbed power). Geometric configurations with uniform simple cross-sectional shapes (line, circle, and elliptical sections), were considered. For each configuration, the body dimensions and submergence, as well as the submergence of the rotation axis, were the optimised variables. They found that most of the optimal geometries have their rotation axes close to the sea bottom and their bodies close to the free surface. The optimal size of the geometries varies depending on the selected wave frequency range, but the optimal cross-sectional dimensions are generally less than one third of the water depth when optimised over a uniform distribution of wave frequencies from 0.4 to 1.3rad/s. Among the cross sections considered, the elliptical one performed best.

Gomes et al. (2010) presented a geometry optimization of the acceleration tube of an IPS (Inter-Project Service) buoy WEC, with the objective of obtaining of a good relation between the energy extracted from a specific wave site and the submerged volume of the device, rather than the objective of power maximisation. The annual average power was found to be insensitive to the PTO damping coefficient for the tube with an optimal geometry. Taking the optimal PTO damping coefficient for each sea state gave an increase of ~4% in the annual produced energy.

Falcão et al. (2012) conducted a hydrodynamic analysis and optimisation of an OWC spar buoy; an axisymmetric device consisting of a submerged vertical tail-tube fixed to an axi-symmetric floater that oscillates mainly in heave. Linear potential flow theory in frequency domain was used. The tube geometry and the air turbine characteristics were optimised. The adoption of a tail tube with a lower segment of larger inner diameter will result in a significant reduction in the optimal tube length and in the turbine coefficient. The volume of the air chamber also significantly affects the optimal tube length, the optimal tube length decreasing with increasing air chamber volume, but not the optimal turbine coefficient.

Control

Control is very important for WECs to achieve good power absorption and acceptable loading under a large range of environmental conditions. Recent developments in the control of WECs and arrays focus on the application of various methods for improved performance in irregular wave conditions.

Latching control has been around since the 1970s and is well-known for improving wave energy conversion efficiency. Current developments in control technologies have focused on how to practically implement the technology. Falcão (2008) proposed a new method to implement latching control and determine the instant when the device is unlatched. Unlike conventional methods, where detailed future information is always preferred, this new technique releases the device once the PTO force is larger than a pre-set value. Similarly, Sheng et al. (2015a) and Sheng et al. (2015b) proposed a new method for implementing latching control in which the latching duration is calculated purely based on sea state parameters, such as the energy period, in such a way that detailed future information is not needed. These new methods are currently sub-optimal and require development; however, they do indicate that the resulting increase in wave energy conversion is significant.

Scruggs et al. (2013) applied Linear-Quadratic-Gaussian (LQG) optimal control theory to WEC control in stochastic seas. Optimal causal controllers were designed for a point absorber and compared to the non-causal and static cases, in terms of the overall power generation performance and spectral characteristics. It was found that for optimal causal controllers, it was necessary that they are gain-scheduled in accordance with changes in the spectral content and direction of the sea state, in order to maintain acceptable power performance.

Sichani et al. (2014) studied the dynamic behaviour of a point absorber considering non-linearities arising from the buoyancy force, geometrical constraints on the motion of the WEC and the saturation loads of the controller. They found that as the maximum available control force decreases the power that could be extracted by the device reduces. For a controller with a high saturation load, there exists an optimal value of PTO damping to obtain maximum power absorption. The inherent addition of stiffness associated with the PTO system decreases the power absorption, but was necessary to constrain the motion of the device.

Bacelli and Ringwood (2013) studied and compared two model-based control strategies for an array of wave energy converters (point absorbers); Global Control (GC) and Independent Control (IC). GC is based on a centralised control algorithm, which uses a complete hydrodynamic model of the array; whereas with IC, each device is controlled independently without considering the hydrodynamic interaction between WECs. Both control strategies apply constraints on the maximum allowable oscillation amplitude and the PTO force. The results indicated that the use of GC in arrays gave an improvement of up to 10% in power performance when compared to independent control. The benefits of GC were greatest for arrays experiencing strong hydrodynamic interaction between individual devices, and for individual devices with strong radiation properties.

Array of devices and park effect

Babarit (2013) reviewed literature related to the park effect for arrays of WECs. The theories and methods that are applicable to wave interaction in arrays of WECs include:

- Analytical methods, only applicable to heaving axisymmetric devices;
- Asymptotic approximations of far field diffracted/radiated waves;
- Numerical models based on boundary element methods;
- Boussinesq and spectral wave models, originally developed for wave propagation over large domains (a few kilometres to hundreds of kilometres).

For small devices (10–20 m maximum dimension), in small arrays (<10 devices), with standard layouts (regular or shifted grids with a separation distance of 10–20 times the characteristic dimension), the park effect was found to be negligible. For larger arrays, however, the number of rows should be minimised to reduce the park effect.

Beels et al. (2010) applied the time-dependent mild-slope equation model MILDwave to study wave propagation and transformation over a farm of five Wave Dragon devices. Based on an assessment of the total power absorption and wave height reduction behind the farm, the optimal layout was found to be a staggered grid (with three WECs in the first row and two WECs in the second row) with a separation distance of 2D (with D the characteristic width of the device). They conclude that this layout does not introduce any losses associated with park effects.

Renzi and Dias (2012a) developed a mathematical model to study the hydrodynamic behaviour and wave power absorption of a bottom-hinged, flap-type, oscillating WEC in a channel. Within the framework of linear inviscid potential-flow theory, analytical solutions were found and validated against available numerical and experimental data. The transverse sloshing modes of the channel were found to enhance the performance of the device near resonance. This theory has been further developed and applied to study the wave interaction of a periodic array of flap-type WECs (consisting of an infinite number of in-line WECs), based on an asymptotic analysis of the far-field waves generated by the array (Renzi and Dias, 2012b). The analytical solutions agree well with the numerical results based on a finite element formulation. Furthermore, a semi-analytical approach was developed for a finite array of flap-type WECs and compared well with a finite-element numerical model based on the software COMSOL Multiphysics for the 2-flap and 3-flap systems with an in-line configuration (Renzi et al., 2014).

Analytical solutions for an analysis of arrays of OWC devices have been considered for the solution of diffraction and pressure dependent radiation problems. Such methods have been used for stationary arrays of interacting devices having cylindrical chambers (Konispoliatis and Mavrakos, 2013a) or annular air chambers (Konispoliatis and Mavrakos, 2013b), as well as for free floating devices (Konispoliatis and Mavrakos, 2014a). Numerical and experimental results concerning exciting wave forces, mean drift loads, air volume flow rate, inner pressure and absorbed wave power were presented for parametric variation of the distance between devices.

Nader et al. (2012) studied the scattered wave field around single and multiple OWCs devices using a finite element formulation and linear wave theory. Power capture efficiency of the single device and of the array was evaluated by parametric variation of the spacing between devices, the pneumatic damping and direction of the incident waves. It was found that the presence of neighbouring OWCs has a significant influence on the power capture efficiency of an individual device, even at large separations. The optimal pneumatic damping for OWCs in an array was potentially found to differ from that of an isolated OWC of the same dimensions.

ULS and FLS analysis

WEC devices are frequently designed to operate in a resonant condition in waves in order to improve power capture which often leads to large motion responses and high risk of wave slamming on the WEC structure near the free surface. De Backer et al. (2010) studied slamming effects on point absorbers in operational conditions for three buoy shapes: two cones with dead rise angles of 45^o and 30^o, and a hemisphere with a waterline diameter of 5m. The difference in peak slamming loads between the 45^o cone and the hemisphere was a factor of 2, while the difference in power absorption was only 4–8%. It is therefore important to consider slamming during the shape design phase, alongside power absorption.

Rogne (2014) studied a hinged 5-body WEC with a shallow draft, cylindrical centre buoy attached to 4 semi-submerged spherical buoys, both numerically and experimentally. Both linear and weakly non-linear hydrodynamic models were applied in the optimisation for power absorption. The weakly non-linear model resulted in a better comparison with the experimental results.

4.1.2 Mooring analysis

There are two distinct types of mooring system for a floating WEC depending on whether it is an integrated part of the PTO system or not. The majority of floating WECs only use the mooring system for station-keeping and therefore the focus in this section is on recent developments in this area.

Recent studies have focused on the influence of the moorings on the performance of the WEC. This is to be expected, since the priority for every WEC is absorption of wave energy in an efficient and profitable manner. It is difficult to draw general conclusions as the findings tend to be specific to a particular type of WEC. The numerical tools used for the analyses are well-established in the offshore industry, as discussed in previous ISSC reports.

A point absorber moored with three chain lines was investigated by Cerveira et al. (2013) to determine the influence of the mooring system on power production. Measured climate data was used to define the sea states. The device extracts energy during the surge and heave modes using two idealised PTO systems represented by linear damping and stiffness coefficients. The dynamics are solved in the frequency domain. Two mooring configurations were examined, slack and moderately slack, along with the un-moored case. It was found that the mooring system reduced the annual energy capture by only around 1%.

Bachynski et al. (2012) used a linearised frequency domain approach to analyse and optimise a tethered WEC in irregular waves. Inertial and damping effects of the mooring system were not included. The results showed that a relatively light mooring system had little effect on the power take-off, but did introduce a low-frequency, coupled, pitch-surge resonance that can cause system failure if subjected to long-period swells.

A two-body point absorber was studied by Muliawan et al. (2013) with the aim of estimating the one-year power production both with and without moorings. A mooring configuration with four, semi-taut, steel wire lines was considered. Two-body hydrodynamic analyses were carried out in the time domain. The effect of the mooring system was implemented using a nonlinear spring. They observed that, as long as the length of the mooring lines could accommodate the motions of the device due to first order wave forces, the effect of the mooring was insignificant. Vicente et al. (2011) also investigated a two-body point absorber. In this case, a slack bottom mooring spread of chains was considered. They also concluded that the mooring system did not significantly affect the absorbed power.

Vicente et al. (2009) assessed an array of point absorbers through a series of numerical simulations, in regular and irregular waves. Three identical hemispherical buoys were considered in an equilateral triangle configuration. The mooring system consists of three spread lines, with a further three lines connecting the buoys to a centrally placed weight. Damping and inertia effects of all of the mooring lines were neglected. The PTO of each floating converter was assumed to be activated by the buoy heaving motion. The dynamics were solved in the frequency domain, without hydrodynamic interaction between the three bodies. It was concluded that the performance was significantly affected by the presence of this tight mooring system.

A positive effect on power conversion relating to the mooring system was discovered by Konispoliatis and Mavrakos (2014b). The objective of the study was an array of closely spaced OWC devices. Three configurations were examined; the devices were assumed to float independently, the devices were connected together forming a freely floating (rigid) multi-device system, and the connected devices were moored as a TLP. The calculations were done in the frequency domain with linearised mooring terms. The authors found that the third configuration absorbs the most wave energy.

In general, energy absorption by oscillating bodies is achieved through various forms of damping. The mooring system however, typically adds damping to the system and the associated energy loss reduces the efficiency of the WEC. Most of the studies described have neglected the damping in the mooring system when evaluating the efficiency of device. Moreover, those that did include it did not consider it to be nonlinear. This is in conflict with the fact that most mooring lines produce non-linear damping (Johanning et al., 2007). Therefore, to gain a more accurate representation of this problem, time-domain methods including non-linear mooring forces are recommended for future analysis.

4.1.3 Power take-off analysis

The power take-off system is a sub-system for converting extracted hydrodynamic energy into useful energy, typically in the form of electricity. Conventional PTO systems can be categorised into four types:

- Hydraulic systems (oscillating bodies);
- Air turbines (oscillating water columns);
- Direct drive generators (oscillating bodies);
- Water turbines (overtopping devices).

Salter et al. (2002) published a summary of PTO systems for wave energy conversion. The first three types of PTOs have been described with respect to applications in the field of practical WECs

(Curran et al., 2008). PTO technologies for wave energy conversion are generally in a developmental stage, with no dedicated mature technologies yet in place. Currently, conversion efficiencies and reliability are both limited when compared to conventional power conversion technologies. The main challenges for most WEC devices include the inherent low speed (roughly in the order of 1m/s), and the oscillatory motion which leads to a large force variation over the cycle. Some devices do not surfer from these problems, however, for example; overtopping devices, cycloidal turbines, and the OWC, which all avoid one or both of these problems. Recent developments in PTO technology have focused on improving the energy conversion efficiency by means of control technologies and strategies.

Kamizuru (2012) compared a number of different applications and PTO developments. In a follow-up paper (Kamizuru et al., 2013), they studied the Hydrostatic Drive Train (HDT) for improved wave energy conversion.

PTO systems for OWCs are more mature than for other types of WECs. These systems are based on self-rectifying (Wells-type/linear) turbines, impulse turbines (nonlinear), or the radial or bi-radial turbine (Falcão et al. (2011), Falcão and Gato (2012)). The first two types have been tested in practical wave energy plants (Takao and Setoguchi, 2012). A large amount of work has been carried out regarding the design of guide vanes for such turbines, which can reach average energy conversion efficiencies of 60–70% for Wells and impulse turbines, and as much as 80% for radial turbines.

Direct drive generators may be applicable to some WEC devices, with similar technology developed for the offshore wind energy industry. In principle, the main difficulties are similar for both applications; a huge power conversion system is required to replace the mechanical gearbox. It should be noted that, for wave energy conversion, direct drive means a linear, reciprocating motion (Mueller et al., 2007). As such, direct drive technology for WECs is more difficult than for wind energy, but some solutions are being developed (Crozier et al. (2011), Serena et al. (2012)).

4.2 Physical testing

Physical testing of WECs includes both laboratory tests at relatively small scales (typically from 1:100 to 1:20) and offshore field tests at larger scales (from 1:5 to 1:1). The purpose of testing is to demonstrate the functionality and survivability of the system and the components, and to obtain information with which to validate numerical models (Cruz et al., 2008). The basic guidelines for physical testing are as follows:

- Initial testing of a system (scale = 1:100–1:50)–hydrodynamic performance and power absorption efficiency, WEC farm performance, and mooring configuration;
- Validation of numerical models or tools (scale = 1:33–1:20);
- Behaviour in extreme conditions (scale = 1:20–1:5)–nonlinear hydrodynamics;
- Functionality and survivability of all components (scale = 1:5–1:1).

Uncertainties and Scale Effects

In any physical modelling scaling issues must be considered, particularly during small scale tests. Hydrodynamically, wave energy converters are similar to conventional ships and offshore platforms where Froude scaling is most appropriate. Sheng et al. (2014) discusses the basic scaling issues for WECs. The most difficult of these involves modelling the PTO system. Sheng et al. (2014) argue that geometrically similar modelling of the PTO system is not generally appropriate because it is usually very difficult, if not impossible, especially at very small scales. Instead, an accurate mathematical model of the PTO should be implemented in the physical model.

PTOs for a Wells turbine can be relatively accurately approximated using a porous membrane, or an orifice for an impulse turbine. However, consideration should be made of the compressibility of air in the chamber (Weber (2007), Sheng et al. (2014), Falcão and Henriques (2014)). In particular, Falcão and Henriques (2014) presented similitude laws for model testing of OWCs concerning geometric, hydrodynamic, thermodynamic and aerodynamic similarity between prototype and scaled-down physical models, with particular emphasis on air compressibility effects and on turbine aerodynamics. It was shown that the correct volume scale ratio for the air chamber should take into account the thermodynamics of the compressible flow through the air turbine. A numerical example was detailed to illustrate the importance of appropriately simulating the air compressibility effects when testing at model scale.

4.2.1 Laboratory testing and validation of numerical tools

With respect to laboratory testing, some of the guidelines and procedures developed by the ITTC for testing of ships and offshore structures are applicable. However, it should be noted that blockage and wall effects are significantly more important for WEC experiments than they are for ship testing, and this should be considered in post-processing and data analysis.

Many model tests have been carried out under the MariNet program. One of the aims of this program is to characterise and verify the performance behaviour of the European test facilities. Results are intended to be used to establish correction factors which can be applied to test results, so that engineers and potential investors can accurately compare the performance of devices tested in different facilities.

In recent years, some well-known WEC concepts have undergone laboratory testing. The Langlee WEC (Pecher et al., 2010) tests focussed on power generation, and the Wave Star point absorber tests (Zurkinden et al., 2014) focussed on the comparison between the numerical and experimental results considering the weakly nonlinear hydrodynamic effects. A recent model test on the Pelamis model was conducted with the goal of reducing the maximum loads on the mooring lines and anchors, the maximum excursions of the device, and the influence on the internal motions which are used for power conversion (Casaubieilh et al., 2014). Two different types of mooring systems were used; a conventional catenary mooring, and a semi taut-leg mooring. The elastic components in the taut-leg system reduced the maximum forces on the mooring line by 67%. The taut-leg system also significantly reduced excursions, while the motions required for power conversion were not affected.

More recent WEC devices have also been tested under controlled conditions in laboratories. Siegel et al. (2012) tested a lift-based cycloidal wave energy converter, CycWEC, at a scale of 1:300 in a 2D wave flume. The experimental results showed an energy extraction efficiency of more than 95% with optimal parameters. Zanuttigh et al. (2013) performed tests of the DEXA device, (www.dexawave.com) a hinged-barge-type concept, with the focus on the influence of various mooring systems on efficiency. Rogne (2014) undertook tests of a hinged 5-body WEC in a small towing tank at Marintek, and studied the effect of nonlinear Froude-Krylov and restoring forces on the platform motions and power absorption. Imai et al. (2014) studied a floating OWC-type WEC, the Backward Bent Duct Buoy (BBDB), endeavouring to understand the effects of various design parameters on the effect of power absorption including the dimension of the duct-extended buoy, the mass of the floater and the shape of the air chamber.

4.2.2 Field testing

A number of devices are currently being field-tested at various scales, though relatively little has been published about these tests due to the commercially sensitive nature of the work. Kofoed et al. (2006) reported the results of the 57m long, 27m wide and 237ton prototype of the Wave Dragon overtopping device at 1:4.5 scale that was tested in Nissum Bredning, Denmark beginning in 2003. The preliminary tests supported the data obtained earlier from laboratory testing and focused mainly on the hydrodynamic performance. Experiences on operational aspects were also obtained from this test campaign, such as regulation strategies for crest freeboard and turbines, and remote control of operation and testing. The power performance of the prototype was investigated by Tedd and Kofoed (2009) indirectly by measuring the overtopping flow time series. Comparison between the simulated and measured data showed that the measurements support the use of the algorithm for generating a simulated flow.

In the Wave Power Project Lysekil, more than 10 prototypes of point absorber WEC have been deployed and tested at the Lysekil research site located on the Swedish west coast since 2006 (Leijon et al. (2008), Lejerskog et al. (2015)). Each WEC has an installed capacity of 10kW and consists of a buoy at the surface, which is connected by a mooring line (steel wire) to a linear generator placed in a capsule on the seabed. Significant research work was carried out with respect to WEC sea tests, analysis of measurement data, comparative study of simulations and measurements, optimization of buoy geometry for wave energy extraction (Sjökvist et al., 2014), performance of large arrays of WECs (Engström et al., 2013). The developed simulation models have been extensively compared with the measurement data and a good correlation between the simulation and the experimental results was obtained for normal operations (Lejerskog et al., 2015). Besides the technical/functional verification and development, the environmental, marine biological and marine ecological aspects the system have also be investigated scientifically (LysekilProject, 2015).

Field testing of various WEC components has also been conducted. Henderson (2006) summarised the test results of a novel hydraulic PTO system for the Pelamis concept, including a 1:7 scale model tested both in a towing tank and at sea, and a full scale prototype with a 1 MW rated hydraulic system tested on a joint test rig. The experiments indicated that the performance of the PTO was as expected, with a combined efficiency of the primary transmission of more than 80% at full scale over a representative range of operating conditions.

Thies et al. (2014) presented field trials from the South West Mooring Test Facility including mooring line fatigue damage results. This facility is a large scale installation designed to investigate mooring loads and responses in real sea conditions. It consists of a generic 3.25ton buoy, that can be moored in various configurations, which has been installed with a three-leg catenary hybrid (rope-chain) mooring since March 2010. It is located in a relatively sheltered site in the southwest part of Falmouth Bay (Cornwall, UK), in a water depth of 27m (low tide mark) and tidal range of up to 5.4m. The installed buoy is extensively instrumented to acquire data regarding the buoy position, motion response and the associated mooring line loads, as well as the wind velocity. In addition, an Acoustic Doppler system is installed nearby to record the environmental conditions including incident waves and tidal currents.

4.3 Rules and standards

Significant efforts are underway to establish rules and standards for WEC development. The main goal is to assess the different technologies on a level playing field to allow for a fair and standardised comparison. For example, most device developers rate their devices using the maximum power output (SI-Ocean, 2012). This can lead to confusion since WECs generally differ from other renewable energy devices in terms of the relation between maximum power output and average power output. Specifically, under design environmental conditions, wind, tidal or solar power will produce consistent power at their rated maximum, while for WECs the average power production will generally be much less than the maximum rated power. Thus it can be misleading to estimate the annual power output for a WEC using the rated power.

In order to correct this problem, several international collaborations have been initiated to establish rules and standards for rating the power of WECs. This should lead to standardised methodologies for assessing different devices so that fair comparisons can be made. Moreover, guidelines, rules and standards should also provide detailed procedures and methodologies for design, testing and operation of wave energy converters.

The International Electrotechnical Commission established the Technical Committee (TC) 114 on *Marine Energy: Wave, Tidal and other Water Current Converters* in 2009, and relevant standards have progressed through several stages. The most advanced standards in wave energy conversion are for resource assessment and mooring system, both of which are in the final stage and the standards are expected to be published in the first half of 2015. More tasks are being carried out by the IEC-TC-114 (2014).

The CarbonTrust (2005) commissioned DNV for a guideline on design and operation of WECs in 2005. This document included many aspects on design and operation of WECs. It should be noted that this document should be regarded as a guideline instead of a standard, but it is hoped that it can be used as a starting point for the future development of standards.

DNV (2008) published the principles and procedures for certification of tidal and wave energy converters in 2008, and made two amendments in 2011 and 2012. The document is built on experience and relevant standards in the oil and gas industry, but also includes the best practices in this particular area. This document is supposed to cover all types of tidal and wave energy converters.

Generally, the technologies for wave energy conversion are still immature, and many devices are in different development stages, while new ideas are continuously being proposed. To guide the rational development of wave energy converters, some best practices have been proposed. Unlike the standards, the best practices are meant to be guidelines on how to move WECs from the concept to the commercial stage, and avoid the most common failure traps.

Under the Implementing Agreement for a Co-operative Programme on Ocean Energy Systems (OES-IA) created by the International Energy Agency, Annex II, Nielsen (2010) published a document entitled “Development of Recommended Practices for Testing and Evaluating Ocean Energy Systems, Summary Report”, in which the design basis and the cost basis for wave and tidal energy systems are discussed. Similarly, the EquiMar project has published many deliverables on their website http://www.equimar.org/. Among the deliverables, two may be more relevant to the topic here: “Best Practice for Tank Testing of Small Marine Energy Devices” and “Protocols and Guidance for Device Specification and Quantification of Performance”. Other relevant information can also be found from the

MariNet project (http://www.fp7-marinet.eu/joint-activity_standardisation-best-practice.html) and the EMEC website (http://www.emec.org.uk/standards/).

5. TIDAL AND OCEAN CURRENT TURBINES

This chapter focusses upon different aspects of tidal energy conversion and ocean current energy extraction. Since 2012, several prototype devices have been deployed in various test locations around the world, with good levels of success. The key to further development of the industry towards a full commercialization is the reduction in uncertainty (and therefore the reduction in cost); be this in device development itself, installation and offshore management, resource modelling or environmental impact assessment.

5.1 Development, modelling and testing of tidal current energy converters

5.1.1 Device development

The previous ISSC reports covered the different concepts available, several of which have been developed into functioning prototypes. Most notably Voith, Atlantis, Andritz Hammerfest, Open Hydro, Marine Current Turbines and Alstom have all deployed successful test devices. Recent developments include a 1MW horizontal axis system from Kawasaki designed for deployment on a gravity base Yanamoto (2012). The turbine is set for test at EMEC, Scotland in 2016 and Japan in 2017.

A Wing-In-Ground effect Turbine (WIGT) concept has been developed (Liu, 2012a). The dual foil unit can be arranged vertically or horizontally (Liu, 2012b), Figure 9. The WIGT has the potential to produce 1.73 times the energy of a conventional Horizontal Axis Tidal Turbine (HATT). It was also found that WIGTs have the ability to improve power capture in shallow water flows and low speed streams.

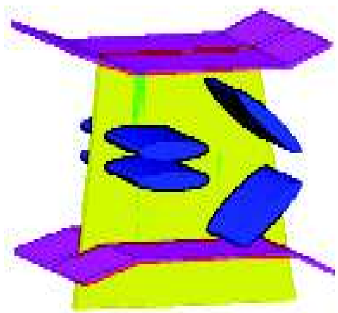

Figure 9. A dual foil arrangement in the WIGT concept (Liu, 2012b).

Some devices have explored the concept of an underwater kite (Lazakis et al., 2013) which improved energy capture in low-speed tidal streams.

An interesting development is increased attention regarding microgeneration systems–whether this be for local schemes in outlying areas or for a number of smaller devices to be coupled to produce a larger yield (Álvarez et al., 2014).

Several prototype HATTs have experienced problems with structural blade failure. In order to optimise rotor structural strength and reliability a procedure was developed by Liu and Veitch (2012) using an example was of a 20m rotor in a flow of 10 knots. The procedure has been so developed that it may be used for both metallic and composite blades. Composite blades have been shown to have the potential to incorporate structured tailoring of the layup so as to result in coupled motions, for example application of a pure bending moment would result in blade twist (Nicholls-Lee et al., 2012). Such coupled deformations can reduce fatigue and prolong service life expectancy. Composite materials are finding favour in more sections of tidal device design; blades have been commonly manufactured from composites for a while, however parts of the support structure, or even the whole foundation, have the potential to gain from use of composite materials in both ease of manufacture and structural integrity (Coppens, 2014).

5.1.2 Numerical modelling and experimental testing

Alongside physical prototyping, modelling of tidal energy converters, both numerically and experimentally, assists design and development of devices in the industry as a whole. Takeda et al. (2013) developed a numerical method of modelling a floating, tethered tidal generator. A joint Canadian-Australian collaboration on a series of bi-directional tidal turbine prototyping, design and optimisation

(Liu and Bose, 2012) resulted in a methodology for generic tidal turbine hydrodynamic prototyping and optimisation. Further work involved a test program on seven selected HATT rotors from the previous series, with a very detailed geometry and motion parameters (Liu et al., 2014b). The work resulted in a key reference platform for tidal turbine design, and measured data for validation of numerical tools.

In addition to the design basis of hydrodynamic performance of the rotor, effects of marine fouling need to be considered as these negatively impact the efficiency of all devices. Tests have been carried out in the waters of Ikitsuki Island, Nagasaki, Japan for eight months to assess biofouling on a small array of three bladed HATTs (Katsuyama et al., 2014). Significant fouling occurred on the uncoated devices and was not affected by turbine rotation. Use of antifouling coatings resulted in only a thin film of fouling.

The effect of array layout is also key to optimising turbine performance. Myers and Bahaj (2012), Bahaj and Myers (2013), Blackmore et al. (2014) discussed the concept of turbines arrangement by experimental studies conducted using multiple actuator disks. Highly turbulent wakes were apparent indicating that optimal lateral spacing as well as the synergistic effect of a downstream row of devices are key for array performance. These results imply that proper design of support structures and arrays optimisation could increase the energy yield as the site-specific turbulence characteristics are taken into consideration.

Numerical assessment of array layout, and the subsequent effect on energy yield has always been a source of interest. This has been carried out a local scale using an actuator disc RANS model (Batten et al., 2013), intermediate scale through adaptive mesh coastal modelling (Divett et al., 2013) and large scale through interpretation of the blockage of a large array of devices in a channel (Vennell, 2012). Staggered arrays were found to show increased energy capture, however increasing the number of rows in an array past the theoretical optimum has harsh consequences due to diminishing returns. Primarily it should be noted that maximising the power production of large arrays is not the same as maximising the conversion efficiency of the turbines.

5.2 Environmental impact

With devices reaching the stage at which deployment into arrays is becoming likely in the near future, concern over the environmental impact of arrays as well as individual devices is increasing. Often the use of potential sites for marine energy extraction are hampered by ambiguities in marine legislation, and high quality Environmental Impact Assessments (EIAs) are therefore imperative (MacLean et al., 2014). Often physical resource assessment and environmental assessment can go hand in hand, with coupled studies reducing time scales and costs relating to marine energy installations (Ashton et al., 2014).

Fauna of interest include fish (Viehman and Zydlewski (2014), Broadhurst et al. (2014)), marine mammals (Worthington (2014), Willis et al. (2013)) and seabirds (Furness et al. (2012), Frid et al. (2012)). Assessment of several impacts through a single study is desirable in order to provide a good coverage of risk in a reasonable time frame. The FLOWBEC seabed platform combines a number of instruments to record information at a range of physical and multitrophic levels at a resolution of several measurements per second, for a duration of 2 weeks to capture an entire spring-neap tidal cycle (Williamson et al., 2014). The interactions between diving seabirds, prey, flow hydrodynamics and tidal energy extraction structures were analysed for a period of five 2-week deployments at EMEC. The results can be used to guide marine spatial planning, device design, licensing and operation.

Other key environmental impacts that must be considered when planning a tidal scheme are those affecting sediment transport (Frid et al., 2012), sand banks (Neill et al., 2012), water quality (Kadiri et al., 2012), and energy removal on the ecosystem (Copping et al., 2013).

5.2.1 Marine planning

The rapid development of the tidal energy sector has led to an increased requirement for Marine Spatial Planning (MSP) and, increasingly, this is carried out in the context of the 'Ecosystem Approach' (EA) to management (Alexander et al., 2012). Conflicts between the interests of tidal energy developers and commercial and recreational users of the area must be identified, and use preferences and concerns of stakeholders considered (Johnson et al. (2012), Alexander et al. (2013), Tweddle et al. (2014)). It is imperative that, in order to provide balance between national and local demands, marine planning is properly carried out, with tools being developed specifically pertaining to this (Janssen et al., 2014).

5.3 Economic feasibility

The choice of which type of electrical power generation technology to adopt is driven by a number of factors including (Johnstone et al., 2013):

- Cost of generated electricity;
- Responsiveness of generating plant to demand;
- Security of supply/resource availability;
- Environmental impact;
- Execution risk.

In the shorter term, in order for tidal energy to gain commercial acceptance, tidal technologies under development need to produce electricity at a competitive price. Key to achieving this is bringing down the cost of installation and operation and maintenance (O&M) of tidal projects. Offshore operations are costly in relatively benign environments, but with the extreme conditions often experienced in tidal locations vessel requirements are onerous and equipment that is suitable is often very expensive to source (Lazakis et al. (2013), Morandeau et al. (2013), Nicholls-Lee et al. (2013)). Modelling of marine operations, incorporating vessel and equipment costs, route analysis, weather windows etc. is imperative to enable proper planning and risk analysis of operations (Lazakis et al. (2013), Morandeau et al. (2013)). Many vessels currently employed in the tidal energy field come from the Oil and Gas sector, and consequently demand high day rates and are often over-specified for the job; i.e. a large amount of unnecessary equipment is present on an overly large deck. There is a requirement for fit-for-purpose vessel to be developed in order to bring installation and O&M costs down, for example the HF4 developed for operation in high currents (Nicholls-Lee et al., 2013), Figure 10, thereby bringing tidal energy closer to economic feasibility.

Figure 10. Purpose-built vessel concept HF4 for tidal turbine installation (Nicholls-Lee et al., 2013).

6. COMBINED USE OF OCEAN SPACE

European waters in the coming years will be subjected to a massive advance of marine energy farms/arrays, and the development of these facilities will increase the need for marine infrastructure to support their installation and operation. The most obvious structures include offshore wind farms, constructions for marine aquaculture, and the exploitation of wave and tidal energy. It is therefore crucial that the monetary cost, use of marine space and the environmental impacts of these activities remain within acceptable limits. Hence, offshore platforms that combine multiple functions within the same infrastructure offer significant economic and environmental benefits. The analysis, design and construction of offshore structures is one of the most demanding set of tasks faced by the engineering profession. The offshore structures have the added complication of being located in an aggressive ocean environment where hydrodynamic interaction effects and dynamic responses become major considerations in their design in comparison to land-based structures. Thus, the analysis, design and construction of offshore structures used for the combined activities in the ocean environment are one of the most important studies that need to be performed (Clément et al. (2002), Boer et al. (2007), Brandon et al. (2010), Menicou and Vassiliou (2010), Da Rocha et al. (2010), Villers and Vigné (2010), Buck (2011), Perez-Collazo et al. (2015)). EU-FP7 funded projects regarding multi-use offshore platforms include TROPOS, MERMAID, H2OCEAN, ORECCA, MAREN2 and MARINA, and are underway for the development of a multi-use platform system integrating a range of technologies.

TROPOS:

Hydrodynamic effects and the dynamic response of offshore structures play an important role in their design. Delory et al. (2011) analysed a multi-disciplinary, multi-platform, observing system for the central-eastern Atlantic ocean using the PLOCAN observatory program. Quevedo et al. (2013) presented a detailed design and analysis of the multi-use platform configuration in the scope of the FP7 TROPOS project. The synergy and the compatibilities amongst the platforms to be used for transport, energy, aquaculture and leisure activities are studied in detail. Lu et al. (2014) analysed the environmental aspect of designing multi-use offshore platforms in the scope of the FP7 TROPOS project.

There are four main components to the platform: Transport, Energy, Aquaculture and Leisure. These are integrated with the aim of enhancing the potential and increasing the added value. Three different platforms configurations are designed in order to form an initial idea of the synergies and compatibilities among components (Quevedo et al., 2013).

MERMAID:

The EU-FP7 funded project MERMAID assessing multi-use offshore platforms is being carried out to develop concepts for the next generation of offshore platforms which can be used for multiple purposes; including energy extraction, aquaculture and platform related transport. The project has undertaken the theoretical examination of new concepts, such as combining structures and building new structures on representative sites under different conditions.

In the analysis four offshore test sites with different environmental characteristics have been carefully selected for their specific challenges. The four sites, representing different environmental, social and economic conditions, are located in different seas. The Baltic Sea, North Sea, Atlantic Ocean and Mediterranean Sea are considered. The most appropriate design options for a given offshore area are being created, and verified, as part of the MERMAID project so that the end users can use the results to aid marine planning strategies.

H2OCEAN:

H2OCEAN is an EU-FP7 funded project assessing the development of an innovative design for an economically and environmentally sustainable multi-use, open sea platform. The main aim is to harvest both wind and wave power for multiple applications on-site, including the conversion of energy into hydrogen that can be stored and shipped to shore as green energy carrier and a multi-trophic aquaculture farm.

The unique feature of the H2OCEAN concept lies in the novel approach for the transmission of offshore generated renewable electrical energy through hydrogen. The concept endeavours to enable effective transport and storage of the energy, decoupling energy production and consumption, thus avoiding the grid imbalance problem inherent to current offshore renewable energy systems. This integrated concept can take advantage of several synergies between the activities present as part of the platform, thereby significantly boosting the environment.

ORECCA:

The ORECCA (Offshore Renewable Energy Conversion platforms–Coordination Action) Project is an EU FP7 funded collaborative project in the offshore renewable energy sector. The principal aim is to overcome the fragmentation of know-how available in Europe and its transfer amongst research organizations, industry stakeholders and policy makers. The objective is to stimulate these communities to take the necessary steps to foster the development of the offshore renewable energy sector in an environmentally sustainable way. The project brings together a combination of experts from a wide variety of multinational companies, research institutions, consultancies, utilities and project developers.

The focus is on European technology, with a specific emphasis on the opportunities that exist across Europe when the three offshore renewable energy sectors within the scope are considered together. Within the ORECCA project, the scope of the offshore renewable energy sector was confined to offshore wind, wave energy and tidal stream. These energy sectors have been identified as those that are currently expected to make significant contributions to the energy system in the medium to long term.

MAREN2:

MAREN2 is an inter-regional project financed by the EC and included in the 2007–2013 Atlantic Area (AA) Programme. The main objective of the project is regarding the exploitation of the renewable energy potential of the marine and coastal environment and protecting, securing and enhancing its sustainability. MAREN2 is focused on the multipurpose platform design, energy uses with other resources, multiple use of facilities and increase stakeholder involvement to minimise negative impact. The activities involved include comparable data collection and processing, multi-purpose renewable energy platform identification and assessment of the hydro-environmental impact of marine renewable energy schemes.

The assessment of the wave energy farm in the Portuguese maritime pilot zone and Atlantic European coasts are analysed in Bento et al. (2014) and Guedes Soares et al. (2014b). A brief review on the feasible business model for the multi-purpose offshore platforms for marine renewable energy and synergies with different technologies is discussed in Karmakar and Guedes Soares (2014).

MARINA:
In the EU FP7 MARINA Platform project, a set of equitable and transparent criteria for the evaluation of multi-purpose platforms for marine renewable energy have been established and applied to select three combined wind and wave energy concepts, from amongst >100 proposed concepts, for detailed study by numerical and experimental methods. These include the spar-torus-combination (STC), the semi-submersible-flap-combination (SFC) and the OWC Array plus one wind turbine. Laboratory tests have been carried out and used for validation of the developed numerical models; for the STC (Wan et al., 2014) with focus on the survivability in extreme wave conditions, for the SFC Michailides et al. (2014) and the OWC Array concept (O'Sullivan et al., 2013) with focus on both the functionality and survivability. In one of the work packages, an atlas of combined wind-wave-current resources has been created for European waters (Cradden et al., 2012) and used in combination with a GIS (Geographic Information System) tool for site selection based on the resources with constraints such as bathymetry and environmental sensitivity. Other aspects of combined renewable energy devices have also been studied in detail in different work packages, such as technology risk assessment, economic feasibility assessment, critical component engineering and grid connection and macro-system integration.

Most of these projects on combined concepts are at the level of conceptual design only. Future work in this direction should focus on technical development and economic feasibility through concept demonstration.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In the past few years, extensive research has been conducted in the area of offshore renewable energy; ranging from conceptual design, numerical tool development, to model-scale and full-scale physical testing. From the industry point of view, offshore wind technology with bottom-fixed foundations is relatively mature and has been successfully applied in the recent development of large-scale offshore wind farms. Floating wind turbine technology has been demonstrated by several prototypes being tested at sea and is progressing with a few small wind farms under planning. Recent experiences in industry indicate that cost reduction is the main challenge for offshore wind development and should be the focus of research work in the future. However, a commercial development of either wave energy or tidal and ocean current energy has not yet taken place. Significant research efforts with clear focus and good continuity are required to develop large-scale wave energy converters or marine current turbines.

Resource assessment is one of the important aspects for developing offshore renewable energy. Generic assessments of wind, wave, tidal and ocean current energy are readily available. Detailed evaluation of resources with sufficient space and time resolutions are necessary for site selection however. This is particularly important for wave and ocean current energy assessment for areas with complex local bathymetry and coastal geometry. Numerical models have been developed for such assessment; however, further validation against long-term measured data is needed. From the structural design point of view, joint environmental data (either measured or hindcast data) of metocean conditions is needed for both ULS and FLS design of offshore wind turbines. Accurate weather forecasting systems are particularly useful for planning transportation and installation of offshore renewable energy devices.

The recent developments in the offshore wind industry show a clear trend towards an increase in size of individual turbines, and wind farms, in order to reduce the costs associated with installation, operation and maintenance. Wind turbines of 5-7MW are now being installed in several wind farms and even larger turbines (8-10MW) are under active development. This calls for a development of optimised or novel support structures, in order to achieve economic feasibility, since these account for a significant part of the total capital cost, especially regarding floating wind turbines.

Numerical tools for dynamic response analysis of both bottom-fixed and floating wind turbines have been developed extensively and rapidly in recent years, by coupling the codes developed originally for the onshore wind industry with those from the offshore oil and gas industry. Developing simplified analysis methods for preliminary design assessment, that are both efficient and accurate, is also needed. A code-to-code benchmark study was carried out under the IEA OC3 and OC4 activities and a code-to-experiment validation is in progress through OC5 using the model test data; however, further validation of the numerical tools against field measurements needs to be carefully planned and thoroughly performed. Due consideration should be given to uncertainties associated with the field measurements of environmental conditions and response parameters.

Further development of experimental methods and techniques for testing of floating wind turbines is needed. This requires associated development of laboratory infrastructure and equipment to generate high-quality wind and wave fields simultaneously. Whilst field testing of some devices is underway, the information obtained from the prototype tests tends to be commercially sensitive and is not often published, therefore there is a need to develop large-scale research centres for testing floating wind turbines at sea. This would be invaluable to both academia and industry alike to aid development of the industry as a whole. The results gained from such centres through the testing of new wind turbine and floater concepts could be utilised for validating numerical tools, testing advanced control systems, applying novel condition monitoring techniques, and gaining experience on installation, operation and maintenance.

Design rules, in particular for floating wind turbines, need further development with details on the use of numerical methods for global and local response analyses considering both normal and fault conditions. Methods or procedures for modelling and analysis of wind turbine faults and their effects on the dynamic responses of offshore wind turbines need to be established, and validated, preferably against field measurements.

Thus far, limited research has been conducted in the field of offshore wind turbine transportation, installation, operation and maintenance. Conversely, a significant amount of offshore work (installing in the order of 500 wind turbines per year) is currently undertaken by the offshore wind industry. The research community may be able to assist in more efficient and economic offshore operations by developing novel methods for installation, O&M and decommissioning which have the potential to be carried out in more severe metocean conditions safely thereby decreasing downtime.

Developing a wave energy converter (WEC), which is commercially viable, is a challenging aim. The recommended method of achieving this is to follow the five development stages from conceptual design through to demonstration of multiple full-scale units, in order to overcome the technological challenges occurring at the different stages of development. In recent years, a significant number of different WEC concepts have been proposed. These have been analysed using numerical methods, or undergone physical testing at model scale or full scale. One key challenge is how to integrate the broad spread of experiences gained through the different industrial and research projects, to further advance the technology development with such a wide range of different design options. It is recommended that this be addressed in future research work. Survivability in extreme wave conditions, and long-term performance with respect to fatigue, are particular challenges for structural design of WECs and also require further investigation.

Numerical tools for the analysis of a single WEC and WEC arrays have been developed. Further validation against model tests is required however; a benchmark study of various numerical tools for analysis of a specific WEC type (either oscillating bodies or oscillating water column) might be beneficial to be performed by the next ISSC committee. Code-to-experiment comparison is preferred. The focus should be given not only to the aspects of hydrodynamics and power absorption for operational conditions, but also to the motion and structural responses in extreme wave conditions.

Developing tidal and ocean current turbines faces a particular challenge due to the conflict between selecting a suitable site with sufficient tidal or ocean current energy resources and finding a suitable time window for installation of these devices. Numerical tools developed so far focused on the assessment of power extraction efficiency and tools for structural response analysis and design need to be developed and validated. Several devices exist and have been tested successfully as full scale prototypes; however, the uncertainties and the costs associated with installation, O&M and decommissioning of the devices are still high. It is recommended that future research be directed in this area, potentially furthering the development of recent novel installation solutions, or improving the infrastructure surrounding key tidal array locations.

Integration of offshore renewable energy solutions with other potential uses of ocean space, such as transport, sea food production, and leisure, are currently being investigated in several EU-funded projects; however, most of these are only at the stage of conceptual design. Future research work is needed to address the plethora of engineering challenges associated with the development of multiuse platforms.

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