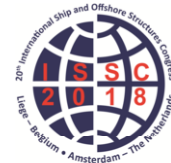


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## COMMITTEE V.4 OFFSHORE RENEWABLE ENERGY

### 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, certification, marine operations and total cost of energy shall be considered.

### COMMITTEE MEMBERS

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### KEYWORDS

Offshore wind turbine, floating wind turbine, wave energy converter, tidal turbine, ocean current turbine, design, integrated dynamic analysis, model test, hybrid testing method, field measurement, marine operations

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## 1. INTRODUCTION

This is the fifth time that ISSC has included the Specialist Committee V.4 Offshore Renewable Energy, which started in 2006. Two-thirds of the committee members for this term (2016-2018) were involved in the work for the previous term (2013-2015), which formulates a good base for the cooperative work in the last three years.

The mandate of the committee was discussed at the beginning of the work and it was slightly modified to explicitly state that the total cost of energy, which has been the central question for developing offshore renewable energy, should be discussed in the committee report. This is important and we allocated one chapter (Chapter 6) to discuss the status of the levelized cost of energy (LCOE) for different energy conversion technologies (offshore wind turbines, wave energy converters and marine current turbines) and the potential for cost reduction in the future through research and development.

It is worth mentioning today's technological maturity and industrial development of different offshore renewable energies. Offshore wind is by far the most developed technology and promising cost reduction has been achieved in the last few years, which makes it possible to consider larger installations at even less cost for the near future. Both wave energy and marine current energy are still in a phase of intensive research and early development. We have seen a number of commercial-size tidal turbines installed for testing in recent years, but very few large-scale wave energy converters.

As compared to the ship and offshore oil & gas industry, the offshore renewable energy community is facing a lot of new challenges in a wide range of research areas, including resource and environmental condition assessment, conceptual design, aerodynamic and hydrodynamic loads calculation, structural response analysis, automatic control, marine installation and operation/maintenance, and various mechanical components. In view of the relevance to ISSC and the competences of the members, we focus on response analysis of offshore renewable energy devices under simultaneous wind, wave and/or current loads for design purposes based on numerical studies, lab and field measurements. Both operational conditions and transit phases such as transport and installation were considered. We have limited discussion about the ultimate and fatigue strengths of these structures (for which similar research on ships and offshore structures can be applicable) and have not considered resource assessment (which was discussed in the previous report) nor electrical grid issues (which are out of the scope for ISSC). Because of extensive research in this field, there exists a vast number of publications that deal with offshore renewable energy technologies. Therefore, the intention was not to cover all of these publications, but to focus on more solid and complete work from reports published by international associations and papers published in well-established journals and proceedings of important conferences.

Three chapters are allocated for three major technologies, i.e. offshore wind turbines (which is the most developed technology and is main focus of our report as in the previous ones), wave energy converters and tidal and ocean current turbines. For offshore wind turbines in Chapter 2, the main discussions are on the development of floating wind turbine concepts, continuous validation of developed numerical codes, new experimental techniques for testing floating wind turbines, as well as marine operations related to transport and installation of offshore wind turbines. The results from a comparative study of optimal offshore wind turbine support structures for varying water depths are presented. Chapter 3 discusses the recent research and development of wave energy converters, with focus on novel concept validation, numerical codes for component and system evaluation, model testing of stand-alone devices and devices in a farm configuration, field testing of a few prototypes, as well as the initial results from the IEA OES benchmark study. In Chapter 4, the recent development of commercial-size tidal current turbines is presented. In particular, numerical methods for turbine loads due to both current and waves are discussed in detail. We also briefly mention the develop-

ment of other technologies for utilization of offshore renewable energy in Chapter 5. The important aspects related to LCOE are discussed in Chapter 6, with focus on the offshore wind industry. In Chapter 7, a short summary of the main conclusions and recommendations for future research are presented.

## 2. OFFSHORE WIND TURBINES

### 2.1 Recent industry development

In the last few years, the offshore wind industry continues to grow and there is a promising significant cost reduction for some of offshore wind farms in the bidding phase. Cost of offshore wind farms will be discussed in detail along with the costs of other offshore renewable energies in Chapter 6. Here, we focus on the industrial development of offshore wind farms.

As shown in Figure 2.1 (GWEC, 2017a), by the end of 2016, the total installed offshore wind capacity reached 14.384GW worldwide and 12.631GW in Europe. Among them, 2.217GW were installed in 2016 worldwide and 1.558GW in Europe, which is 39% less than those installed in 2015 worldwide and 48% less in Europe. However, the number of offshore wind farms under construction and planned indicates a promising increase in installed capacity for the coming years (BVGA, 2017). Most of the offshore wind farms installed are located in Europe (in particular in the UK and Germany). There was a significant development in China in recent years, which lead China to be the third largest country in terms of installed offshore wind capacity in 2016, replacing Denmark. The US built their first offshore wind farm (The Block Island Wind Farm) in 2016, with five 6MW Alstom Haliade wind turbines on jacket foundations.

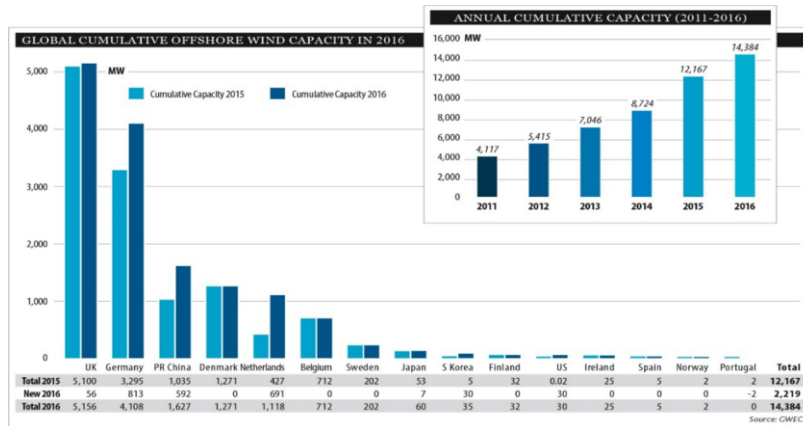


Figure 2.1: Global installed offshore wind capacity in 2016 (GWEC, 2017a)

The recent trend of offshore wind development shows that more wind turbines are being installed in deeper waters, farther from shore and in a bigger farm configuration. Most importantly, the rated power and the turbine size are continuously increasing. The average rated power for those installed in 2016 is 4.8MW (WindEurope, 2017), which is a 15% increase as compared to those in 2015. The first 8MW turbines (thirty-two Vestas' V164 turbines, with a rotor diameter of 164 m) have entered the market in 2016 and have been installed at the Burbo Bank Wind Farm Extension in the Irish Sea in UK. As shown below in Figure 2.2, the trend of increasing turbine size seems to continue, which will be beneficial to the overall cost reduction, but will lead to a lot of challenges for offshore installation, due to longer blades and larger lifting height.



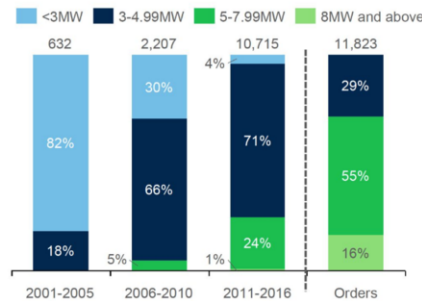


Figure 2.2: Increasing size of offshore wind turbines through years (Green Tech Media, 2017)

In the recent years, floating wind turbine technology has further developed. With the first small farm of five 6MW spar wind turbines installed by Statoil in Scotland (Statoil, 2017a), an important step towards the commercialization of floating wind farms was achieved. As per the presentation from Moeller (2017), in the next several years, a number of floating offshore wind projects will be commissioned, as shown in Figure 2.3. This includes the existing prototypes in Norway, Portugal and Japan and a few more prototypes that are already under construction in Japan, France and Germany. In addition to the Statoil Hywind Scotland wind farm, two small floating wind farms will be developed under the WindFloat 2 project in Europe and the Maine Aqua Ventus I project in the US.

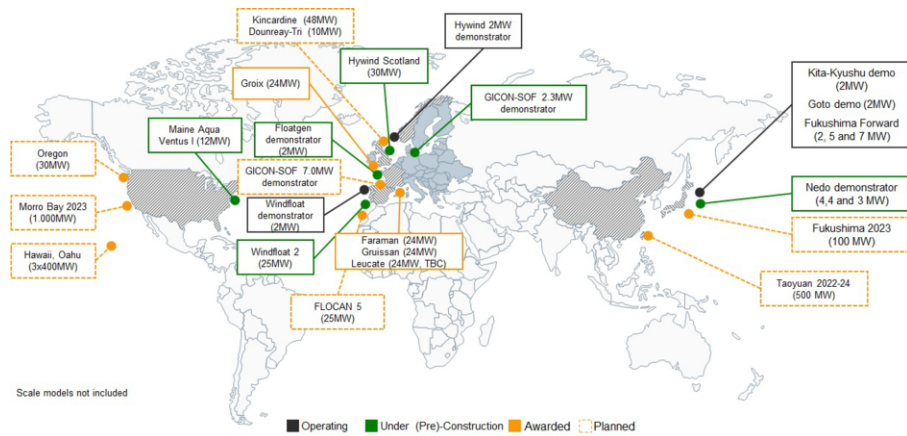


Figure 2.3: Current market situation of offshore floating wind turbines (Moeller, 2017)

As for long-term plans, the European Union set a legally binding target in 2014, to achieve at least 27% renewable energy in final energy consumption in Europe by 2030, which corresponds to 46-49% of electricity generated by renewables (EC, 2017). Accordingly, a wind energy development scenario towards 2030 was presented by EWEA (2015) and indicates that the total installed capacity of wind power could reach 320GW in 2030, comprising 254GW of onshore wind and 66GW of offshore wind. If we consider the total installed offshore wind capacity of 12GW up to 2016, an average annual increase of 15% is needed to reach this goal. This is probably achievable in view of the average annual increase of 25-30% in recent years. However, it also implies a significant number of offshore wind turbines that need to be installed, which is in the order of 650 6MW turbines per year.

Outside Europe, both China and the US have the potential and also the plans for offshore wind development (GWEC, 2017b).

China has a long coastline with rich offshore wind resources and the estimated technical potential of offshore wind power in China within 50km range offshore is up to 758GW (Wen, 2016). After several years of development, China's offshore wind farms have begun to take shape. In 2016, China was ranked as No. 3 in terms of the total installed capacity. In comparison with the total installed offshore wind capacity of 1.63GW by 2016, the Chinese government aims to achieve the total capacity of 5GW installed and 10GW under construction by 2020 (Offshore Wind, 2017).

In the US, the total technical potential of offshore wind in the five coastal regions (North Atlantic, South Atlantic, Great Lakes, Gulf of Mexico and Pacific regions) are estimated to be 2059GW (Musial et al., 2016). On the other hand, there is a big market for electricity demand in these coastal regions in the next thirty years, as indicated in Figure 2.4 by Marcy & Beiter (2016). The figure shows the difference between the electricity projected to be generated by various power plants and the projected electricity demand along the US coastlines. Thus, it shows the opportunity for energy developments, which in some regions offer potential for offshore wind farms. The North Atlantic coast of the US has the best potential for further development because of the proximity to high demand centers, relatively shallow waters, and higher wind speeds. Presently several projects are in the planning stages in the US, including the 90MW South Fork Wind Farm off the coast of New York and the 120MW wind farm offshore Maryland.

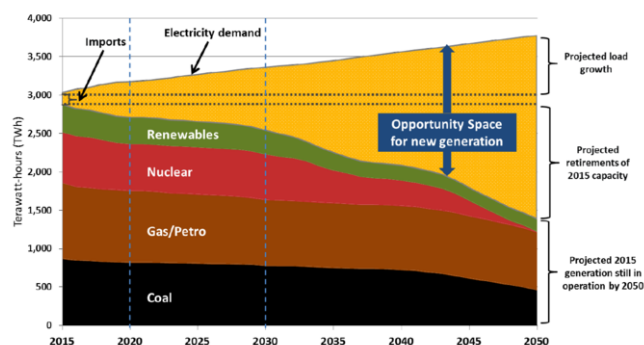


Figure 2.4: Future projected electricity demand and generation in the US coastal regions with the difference being the ‘opportunity space’ (Marcy & Beiter, 2016)

## 2.2 Numerical modelling and analysis

### 2.2.1 Numerical tools – state-of-the-art and validation

In the last decade, many numerical tools were developed for coupled dynamic analysis of both bottom-fixed and floating wind turbines for design purposes. Validation of numerical codes is an important step before they are widely used in the industry.

The International Energy Agency (IEA) initiated a code validation study through Wind Tasks 23 and 30, called OC3 (2005-2009) and OC4 (2010-2013), with focus on code-to-code comparison. As a continuation, the current OC5 (Offshore Code Comparison Collaboration Continuation, with Correlation) (2014-2018) project aims for validation of offshore wind modelling tools through the comparison of simulated responses to physical response data from actual measurements. It consists of three phases, including Phase I using the data for validation from the model-scale tank tests of monopile foundations at MARINTEK (Robertson

et al., 2015) and at DHI (Robertson et al., 2016), Phase II comparing the data from the model test of a semi-submersible floating wind turbine at MARIN (Robertson et al., 2017) and Phase III considering the field measurement data of a jacket wind turbine from the Alpha Ventus Wind Farm in Germany.

The work in Phase I has been concluded. The Phase II work was completed in mid-2017, but no reports were available at the time of this report writing. In 2018, they will focus on the Phase III comparison. Therefore, we discuss some of the Phase I results in our report. This benchmark study attracts most of the code developers and users for offshore wind turbine analysis and therefore it will be interesting and important to follow up this benchmark study for the future ISSC committee.

In the ISSC report (Brennan et al., 2012) in 2012, we discussed the codes that were compared in the OC3 and OC4 studies. It should be noted that most of the codes in this benchmark study were the global loads and response analysis codes. Wind turbine aerodynamics in such codes are based on the Blade Element Momentum (BEM) theory, while hydrodynamics are based on potential flow theory or the Morison's formula. The codes also have the ability to do platform motion and structural response analysis. Table 2.1 shows the codes that participated in the OC5 Phase I comparison against the results of a flexible monopile under wave loads from the model test at DHI (Robertson et al., 2016). Since this phase focused on linear and nonlinear hydrodynamic loads on a flexible monopile, the main features of wave kinematics models and loads models are compared in the table. Most of the codes are now able to simulate nonlinear waves in both regular and irregular seas and the hydrodynamic loads are mainly based on the Morison's formula. Typically, finite element models are implemented in these codes to capture vibrational responses, which are important for offshore wind turbines.

Figure 2.5 shows the monopile model considered in the test (which was designed so that the first bending mode of the structure was properly scaled). The time series of the wave elevation and the total shear force at the bottom are compared in the figure for large irregular waves ( $H_s=0.104\text{m}$ ,  $T_p=1.4\text{s}$  at model scale and  $H_s=8.32\text{m}$ ,  $T_p=12.5\text{s}$  at full scale) of moderate water depth ( $0.51\text{m}$  at model scale and  $40.8\text{m}$  at full scale). The comparison was made directly at the model scale and the scaling ratio was 1:80. Most of the codes can predict well the nonlinear wave elevation and the corresponding loads under the non-breaking condition. This is also shown in Figure 2.6 (top plot) by the exceedance probability of the total shear force. However, the numerical predictions deviate more significantly from the measurements for breaking waves ( $H_s=0.133\text{m}$ ,  $T_p=1.56\text{s}$ ) in shallow water (with a depth of  $0.26\text{m}$  at model scale), as shown by the exceedance probability of the total shear force in the same figure (bottom plot).

Individual code developers are also doing code validation against different types of model test and field measurements. These research activities are discussed below in the sections of analysis for bottom-fixed and floating wind turbines, as well as physical testing.

Classification societies are developing guidelines or recommended practice for coupled analysis of floating wind turbines, such as the JIP run by DNV-GL (2017a). This guidance will include setting up minimum requirements for the design of new concepts that can help investors' evaluation, and supporting the more mature technologies towards a safe and secure commercialization. It also covers the methodology to validate numerical models in relation to requirements in the standards from tank test results.

### *2.2.2 Loads and response analysis of bottom-fixed wind turbines*

Bottom-fixed wind turbines are installed in the majority of today's offshore wind farms. The technology related to bottom-fixed wind turbines is relatively mature. Therefore, the research focuses on different aspects of wind turbine analysis where large uncertainties still exist (including soil-pile interaction, nonlinear wave loads) or where efficient methods are needed (for example for fatigue analysis or optimization).

Table 2.1: Numerical codes benchmarked in OC5 and their features (Robertson et al., 2016)

Participant	Code	Wave Model (Reg/Irr)	Wave Elevation	Hydro Model	Structural Model	Number DOFs
4Subsea	OrcaFlex	FNPF kinematics	FNPF kinematics	ME	FE, RDS	160 elements 960 DOFs
GE	Samcef Wind Turbines	5 <sup>th</sup> -Order Stokes/ Linear Airy	Stretching	ME	FE (TS), RD	13 elements 84 DOFs
DNV GL-ME	Bladed 4.6	6 <sup>th</sup> - and 8 <sup>th</sup> -Order SF/ Linear Airy	Measured	ME	FE (TS), MD	8 (CB)
DNV GL-PF	Bladed 4.6	Linear Airy	Measured	1 <sup>st</sup> Order PF	Rigid	N/A
DTU-HAWC2	HAWC2	6 <sup>th</sup> -and 8 <sup>th</sup> -Order SF/Linear Airy and FNPF kinematics	Stretching and FNPF kinematics	ME	FE (TS), RDS	20 elements, 126 DOFs
DTU-HAWC2-PF	HAWC2	6 <sup>th</sup> -and 8 <sup>th</sup> -Order SF/Linear Airy	Stretching	McCamy & Fuchs	FE (TS), RDS	31 elements, 192 DOF
DTU-BEAM	OceanWave3D	FNPF kinematics	FNPF kinematics	ME+Rainey	FE (EB), RD	160 DOFs
IFE	3Dfloat	FNPF kinematics	FNPF kinematics	ME	FE (EB), RDS	62 elements, 378 DOFs
IFE-CFD	STAR CCM	CFD	CFD-derived	CFD	Rigid	N/A
IFP-PRI	DeeplinesWind	3 <sup>rd</sup> -Order SF/ Linear Airy	Measured	ME	FE	200 elements
UC-IHC	IH2VOF	FNPF kinematics	FNPF kinematics	ME	Rigid	N/A
MARINTEK	RIFLEX	2 <sup>nd</sup> -Order Stokes and FNPF kinematics	Measured and FNPF kin.	ME	FE(E-B), RDS, FS	167 elements, 1002 DOFs
NREL-ME	FAST	2 <sup>nd</sup> -Order Stokes and FNPF kinematics	Measured and FNPF kin.	ME	FE (TS), MD	4 (CB)
NREL-PF	FAST	2 <sup>nd</sup> -Order Stokes	Measured	2 <sup>nd</sup> -Order PF	Rigid	N/A
NTNU-Lin	FEDEM 7.1	Linear Airy	None	ME	FE (EB), RD	13 elements, 84 DOFs
NTNU-Stokes5	FEDEM 7.1	5 <sup>th</sup> -Order Stokes	None	ME	FE (EB), RD	13 elements, 84 DOFs
NTNU-Stream	FEDEM 7.1	Stream Function	None	ME	FE (EB), RD	13 elements, 84 DOFs
PoliMi	POLI-HydroWind	2 <sup>nd</sup> -Order Stokes	None	ME	FE (EB), RD	23 elements, 69 DOFs
SWE	SIMPACK +HydroDyn	2 <sup>nd</sup> -Order Stokes	None	ME	FE (TS), MD	50
UOU	UOU + FAST	2 <sup>nd</sup> -Order Stokes	None	ME	Rigid	N/A
WavEC	Wavec2Wire	2 <sup>nd</sup> -Order Stokes	Measured	2 <sup>nd</sup> / <sub>1</sub> <sup>st</sup> - Order PF	Rigid	N/A
WMC	FOCUS6 (PHATAS)	FNPF kinematics	FNPF kinematics	ME	FE (TS), MD	12 (CB)

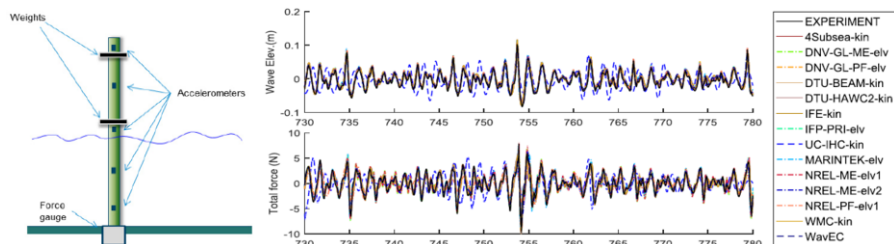


Figure 2.5: The flexible test model (left) and examples of wave elevation (middle, top) and total shear force (middle, bottom) at the monopile bottom for large waves ( $H_s=0.104\text{m}$ ,  $T_P=1.4\text{s}$  model scale ( $H_s=8.32\text{m}$ ,  $T_P=12.5\text{s}$  full scale)) in moderate waters (with a depth of  $0.51\text{m}$ , model scale ( $40.8\text{m}$  full scale)) (Robertson et al., 2016)

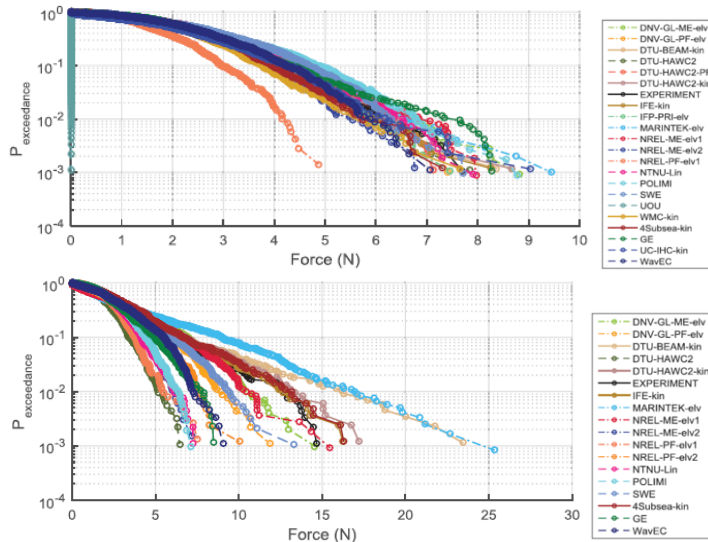


Figure 2.6: Exceedance probability of the total shear force at the monopile bottom under non-breaking waves in moderate water (top) and breaking waves in shallow water (bottom) (Robertson et al., 2016)

**Soil-pile interaction**

The p-y curve approach is the commonly applied method for analyses of laterally loaded piles. With its heritage from the offshore oil & gas industry, where the loading situation is substantially different and piles with smaller diameters are used as compared to offshore wind, such method is not suitable for large-diameter monopile foundations for offshore wind turbines. In the PISA (Pile Soil Analysis) project (Byrne et al., 2015), a new design methodology for monopile foundations was developed to overcome the shortcomings of the current methods. This new design method, as shown in Figure 2.7, is based on the use of numerical finite element models which are validated through a campaign of large scale field tests.

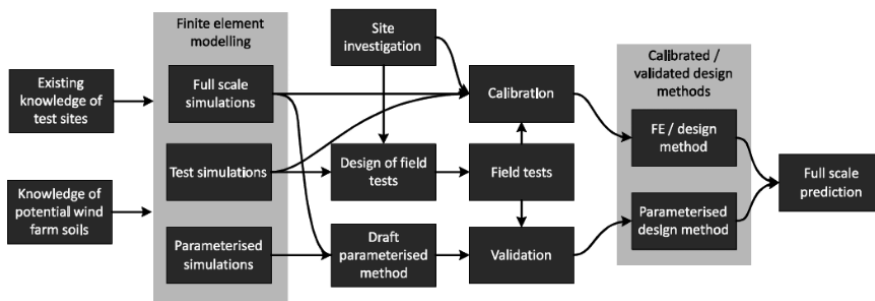


Figure 2.7: The new design methodology developed in the PISA project (Byrne et al., 2015)

The numerical analysis of the long-term performance of offshore wind turbines supported by monopiles is performed by Ma et al. (2017) considering cyclic loading of wind and waves. The study shows that under the serviceability limit state, the deflection and rotation at pile head considering the effect of long-term cyclic loading are notably greater than those computed for the case where this long-term effect is ignored.

### ***Nonlinear wave loads and seismic loads***

Bottom-fixed wind turbines installed in the shallow water regions are exposed to nonlinear wave loads. The breaking wave forces on jacket type structures and slamming wave loads on truss structures were analysed by Jose et al. (2016a, 2016b). In the case of jacket structures the wave kinematics calculated by the CFD model show a very good agreement with the experimental results. However, the CFD model overestimates slightly the total force calculations compared with the experimental results.

Wei et al. (2017) analyzed the dynamic effects in the response of offshore wind turbine supported by jackets under wave loading considering series of time domain dynamic analysis based on loading from regular and irregular wave histories and OWT support structures. The study shows that the dynamic amplification factor decreases with the increase in wave height.

Morato et al. (2017) studied the ultimate loads and responses of a monopile supported offshore wind turbine using fully coupled simulations. The structural response to different ultimate limit states is analyzed and the design load cases are ranked based on the three response parameters.

Horn et al. (2016) identified that hydro-elasticity contributes to the fatigue damage on large volume monopiles in the offshore wind energy industry. The study shows that the large third/fourth order moment and fatigue contribution is due to an incident wave elevation influenced by the sum-frequency components.

The offshore wind turbine model resting on multiple piles under seismic, wind, wave and current loads is investigated by Wang et al. (2017) and it is observed that the structural responses increase proportionally under the normalized seismic excitations with different peak ground accelerations.

### ***Fatigue analysis and optimization***

In the SLIC (Structural Lifecycle Industry Collaboration) project, a number of fatigue tests were carried out for welded steel foundations (such as monopile) for offshore wind turbines in air and seawater (Mehmanparast et al., 2017). It was found that for a given value of the stress intensity factor range ( $\Delta K$ ), the fatigue crack growth rate ( $da/dN$ ) is on average around 2 times higher in seawater compared to the rate in air for the base metal and weldments, which is almost half of the value recommended by the current standards.

Ziegler et al. (2016) presented the influence of load sequence and weather seasonality on the fatigue crack growth for monopile-based OWT. The study indicates that loading sequence does not influence the long-term crack propagation considering fatigue relevant load cases only.

Muller et al. (2016) presented the study on the validation of load assumptions for both fatigue and ultimate loads. The study showed that, as compared to the wind loads, the wave loads have less influence on the structural responses at the tower base and even at the locations of the upper jacket.

Ong et al. (2017) investigated the dynamic responses of two jacket-type offshore wind turbines using both decoupled and coupled numerical models under wind and wave loadings. In the decoupled model, the thrust and torque of an isolated rotor model are used as wind loads and in addition a linear aerodynamic damping effect is considered.

The correlation between the tower top axial acceleration and the load effects in drivetrain segments of a monopile offshore wind turbine is investigated by Nejad et al. (2016). The study shows no correlation between the maximum axial force in the drivetrain and the maximum axial acceleration at the tower top. The tower-top bending moment was found to increase as the wind increases.

Wind turbine foundation optimization (monopile, jacket or floating foundations) is a hot topic in recent years. Considering the fact that there is a large number of simulations required for design analysis, such optimization analysis relies on the development of efficient numerical methods, for example those based on frequency-domain models.

Feyzollahzadeh et al. (2016) presented the responses of a wind turbine due to wind loads acting on it using an analytical transfer matrix method (TMM). The comparison of TMM result with the conventional methods shows that TMM can be used for the wind induced vibration analysis of the wind turbine as it gives a high value of accuracy.

Chew et al. (2016) developed an analytical gradient-based optimization framework for the design of OWT support structure, minimizing the overall structural mass and considering the design checks for member sizing, eigen-frequencies, extreme and fatigue load effects as constraints. It was applied to the UpWind and OC4 jacket wind turbines, supporting the NREL 5MW rotor. The optimization analysis was carried out with respect to diameter and thickness of the jacket legs and braces. Figure 2.8 shows the results of the initial and optimal designs obtained using both the analytical method and the central difference numerical method.

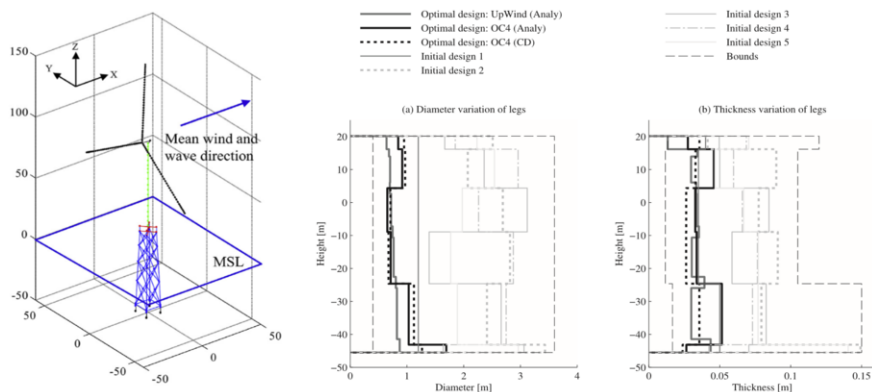


Figure 2.8 Initial and optimal designs of the UpWind and OC4 jacket support structures (Left: jacket wind turbine; middle: diameter of legs; right: thickness of legs. Analy: analytical method; CD: central difference method.)

### 2.2.3 Loads and response analysis of floating wind turbines

In the recent years, a significant number of studies on offshore floating wind turbines for deep waters (with a depth more than 50m) have been performed. The development and installation of multi-MW wind turbines started in early 2000 and are still in progress. Various floater concepts are developed and analysed to understand the dynamic behaviour under simultaneous wind/wave/current loads and to find a cost-effective solution. The focuses were on the development of novel floater concepts, CFD analysis of floating wind turbines, mooring system design and analysis, etc.

#### **Global response analysis**

Different modelling techniques to predict loads acting on the offshore floating wind turbines and induced motions and structural responses have been proposed and applied. Nygaard et al. (2016) presented the theory behind the structural model, aerodynamic and hydrodynamic load modules, control system and coupling with an optimizer. The verification and validation of the code 3DFoat for a floating platform was performed. Guignier et al. (2016) presented multibody modelling of a floating offshore wind turbine foundation for global load analysis induced by wind and wave loads. The validation of the numerical model was performed by



comparing the obtained results with the classical rigid body floater model. Lemmer et al. (2016) presented a linear time-invariant (LTI) model for a floating wind turbine (FOWT) coupled with a linear structural FOWT model. The LTI model fitted to the linear wave excitation force coefficient from a panel code which has been compared to the original panel code data in frequency and time domains.

Most of the developed floating wind turbine concepts are either spar, semisubmersible or TLP floaters. The dynamic characteristics of the truss Spar-type floating foundation used to support the offshore vertical-axis wind turbine (VAWT) were analyzed by Liu et al. (2016b). The effects of foundation parameters on the hydrodynamic performance of the offshore floating foundation were investigated. The motion performances were analyzed and compared for the two floating VAWTs, S-1 (the VAWT supported by FS-1) and S-2 (the VAWT supported by FS-2).

Leimeister et al. (2016) examined the procedure of up scaling of a semi-submersible platform in order to support a predefined wind turbine. The stability analysis, frequency-dependent hydrodynamic coefficients, natural periods and motion responses of the floating semisubmersible platform are thoroughly investigated under this study. Luan et al. (2016) explained the design data and numerical analysis of a braceless steel semi-submersible wind turbine. A numerical analysis is performed to analyze the intact stability, natural periods and modes and global dynamic responses in the combination of wind and waves. Wandji et al. (2016) developed a semi-floater concept for installation of a floating offshore wind turbine support structure under a moderate water depth. The reliability analysis and fatigue load calculations are performed to ensure a desired life expectancy of the structure. It is shown that the semi-floater design is fulfilling the necessary design requirements for supporting floating wind turbines. Karimirad and Michailides (2015) examined a V-shaped braceless semisubmersible wind turbine, similar to the concept of Fukushima FORWARD.

Walia et al. (2017) performed a FAST simulation for a TLP substructure with new material. It was shown that the deflections for all six DOFs are very small for the operating status as well as for an extreme storm surge. As one important result of the paper, the resulting internal forces and moments at the transition piece from the FAST simulations were taken as an input for the analyses of the steel reinforced pre-stressed ultra-high performance concrete pipes. These assumptions are conservative, and further investigations are needed.

Hydrodynamic effects, including second-order wave loads and viscous effects, on the motion responses of floating wind turbines are still being studied in detail. Antonutti et al. (2014) have shown the importance of including the heave plate excursion effects as a result of wind-induced inclination in a semi-submersible FOWT. Lopez-Pavon and Souto-Iglesias (2015) discussed hydrodynamic coefficients and pressure loads on heave plates for semi-submersible type FOWT using large scale models (1m diameter discs).

Liu et al. (2016c) examined modelling of a semi-submersible with slender bracings. Four different numerical methods (pure panel method, pure Morison's formula, combination of panel method and Morison's formula where inertia forces for slender bracings are modelled either by Morison's formula or panel method) are compared with experiments.

Karmakar et al. (2016) analyzed the reliability-based design loads based on the environmental contour method to estimate the long-term extreme loads for FOWT of spar-type and semi-submersible-type. In the case of 1D model, 10-min mean wind speed was considered as random, whereas wave height and 10-min maximum response load were held at their mean levels. In the case of 2D model, 10-min mean wind speed and wave height was considered random while the load variable was considered to be deterministic at its mean level. Basically, 1D and 2D models gave consistent results for the design loads.



### ***Fatigue analysis***

Considering the fact that thousands of time-domain simulations need to be carried out for fatigue design of wind turbines, developing efficient simulation techniques or numerical methods are always interesting.

Kvittem and Moan (2015) dealt with fatigue analysis for a semi-submersible wind turbine. Here, a wide range of environmental conditions were considered in order to study the effect of simulation length, the number of realizations of wind and wave loads, bin size and wind-wave misalignment.

Graf et al. (2015) proposed a high-throughput computation method in fatigue load estimation of floating offshore wind turbines using a Monte Carlo integration instead of using traditional grid-based methods. They showed that the Monte Carlo integration method can reduce the number of aeroelastic simulations drastically, but as nonlinearity increases, the effectiveness of the Monte Carlo approach is reduced.

Nejad et al. (2015) performed load and fatigue damage analysis of drivetrains in floating wind turbines of TLP, spar and semi-submersible. A de-coupled analysis approach was employed for the drivetrain analysis. First, the global response analysis was made, and motions, moments and forces from the global analysis were applied on the gearbox multibody model.

### ***CFD analysis of floating wind turbines***

Nowadays, a common approach for evaluation of aerodynamic loads acting on an offshore wind turbine is based on blade element momentum theory (BEMT). On the other hand, a common approach for hydrodynamic analysis for floating wind turbines is to use either the Morison's formula, potential flow theory or combinations thereof. However, alternative CFD approaches might be used possibly for validation of the above-mentioned methods. CFD calculations of aerodynamics and hydrodynamics are expensive and not suitable for engineering design in which a significant number of load cases need to be simulated. However, they are useful for special loading conditions for which detailed flow around the aero-foil and the floater needs to be resolved. For example, for a floating offshore wind turbine, the motion of a floating body may affect the flow fields, and thus the underlying assumptions in BEMT might be violated.

Sant and Cuschieri (2016) compared three aerodynamic models – the blade element momentum theory (BEM), the general dynamic wake (GDW) method implemented in FAST and a free-wake vortex method (FWVM) - for predicting the thrust and power characteristics of a yawed floating wind turbine rotor.

Liu et al. (2016d) investigated the effects of platform motions on the aerodynamics of a FOWT using the open source CFD code OpenFOAM. The aerodynamic thrust and torque on the wind turbine are compared and analyzed for platform motion patterns with the flow field.

Tran and Kim (2015) studied the periodic pitching motion caused by the rotation of turbine blades. The unsteady computational fluid dynamics (CFD) simulation based on the dynamic mesh technique is used for analysis of the pitching motion of wind turbine due to the platform motion. Tran and Kim (2016) then performed an unsteady aerodynamic analysis for both the blade alone and the full configuration wind turbine models considering the periodic surge motions of a floating wind turbine platform using both CFD and unsteady BEM.

Jeon et al. (2014) investigated the flow states of a floating wind turbine during platform pitching motion using the vortex lattice method. They showed that a turbulent wake state, which is unwanted aerodynamic phenomena, may arise when the floating platform is pitching in the upwind direction.

Quallen et al. (2014) performed CFD simulations of the OC3-Hywind model using a quasi-static crowfoot mooring-line model. They compared the results with the predictions by the NREL FAST code. Dunbar et al. (2015) developed and validated a tightly coupled CFD/6-DOF solver using the computational continuum mechanics library OpenFOAM, and then applied it to the DeepCwind semisubmersible offshore floating wind turbine platform. They also compared the results with the NREL FAST/HydroDyn code.

Leble and Barakos (2016a; 2016b) presented the study on the hydrodynamics load computation on the supporting structure using the Smoothed Particle Hydrodynamics (SPH) method and the aerodynamic load computations are performed using HMB3 CFD solver. The coupled analysis is performed for offshore wind turbine and it is showed that the weak coupling is adequate for the load computations.

### ***Mooring system design and analysis***

Lopez-Pavon et al. (2015) examined time-domain simulations with different models for the second-order forces for catenary mooring design of a semi-submersible FOWT. The models were full 6DOF quadratic transfer functions (QTF), Newman's approximations (6DOF), no slow-drift forces, and full 2DOF QTFs. Comparison between numerical and experimental results showed that, although the main trend is well captured by the numerical estimations, numerical results under predicted the measured loads to some extent, even when full 6DOF QTFs were computed.

Hall and Goupee (2015) introduced a lumped-mass mooring line model with DeepCwind semisubmersible FOWT, and validated it against scale-model test data. For the uncoupled validation, in which the fairlead kinematics are prescribed based on the test data, the mooring line tension at the fairlead agreed well with the experimental data. In coupled simulations of the entire FOWT system, the surge and pitch motions agreed well with the test data, but the heave motions were under predicted.

Gutierrez-Romero et al. (2016) presented a non-linear FEM solver for the analysis of the response of moored floating structures, in particular floating wind turbines. The model was based on an updated Lagrangian formulation. The OC3-Hywind FOWT was analyzed under operational conditions considering second-order waves. The results suggest that using a quasi-static model for fatigue assessment of the mooring lines could overestimate their fatigue life, whereas a first-order seakeeping approach could underestimate tension values on the mooring systems.

Azcona et al. (2017) quantified the influence of mooring dynamic models (either dynamic or quasi-static) on the calculation of fatigue and ultimate loads of three offshore FOWTs (spar, semisubmersible and tension-leg platform). More than 3500 simulations for each platform and mooring model were launched and post-processed according to the IEC 61400-3 guideline (IEC, 2009). It was revealed that the additional damping introduced by the mooring dynamics plays an important role on the differences of the models.

Hsu et al. (2017) investigated the extreme value distributions of a FOWT mooring tensions, where special attention was paid to snap-induced tensions in mooring lines. A composite Weibull distribution model with different shape and scale parameters was proposed that appeared to fit available data well.

### ***Floating vertical axis wind turbines***

Paulsen et al. (2014) summarizes the results from the DeepWind project on the development of a 5 MW spar vertical axis wind turbine (VAWT), with focus on the state-of-the-art design improvements, new simulation tools HAWC2 and results, and the feasibility for up-scaling to 20 MW. The aspects on structural mechanics, generator, floater & mooring system, control system design and rotor design were discussed in detail using the integrated tools. The design

has a rotating floater (spar) and the study found that the Magnus forces on the rotating floater have a limited influence.

Wang et al. (2016a) presented a stochastic dynamic response analysis of a 5MW floating vertical-axis wind turbine (FVAWT) based on fully coupled nonlinear time domain simulations. They used Simo-Riflex-Double Multiple Streamtube (DMS) coupled solver under different environmental conditions.

An integrated numerical tool (Simo-Riflex-AC) was developed for modelling and analysis of floating vertical axis wind turbines (Cheng et al., 2017a; 2017b; 2017c). AC stands for Actuator Cylinder flow model for aerodynamics of VAWT. The AC model was validated against experimental data and compared to another model DMS (Double Multiple Streamtube). The numerical model was used to study a VAWT with a two-bladed Darrieus rotor and found that the 2P (twice per revolution) responses are significant. Increasing the number of blades from 2 to 3 and 4 would reduce such responses. It is also used to compare the responses of a VAWT and a horizontal axis wind turbine (HAWT).

Borg and Collu (2015a) presented a literature review to understand the coupled dynamics involved in floating vertical axis wind turbines (VAWTs). They focused on the approaches to develop an efficient coupled model of dynamics for floating VAWTs. Emphasis was also placed on utilizing computationally efficient models and programming strategies. Borg and Collu (2015b) investigated the frequency-domain characteristics of floating vertical axis wind turbine aerodynamic loads. They presented through a case study the influence of unsteady platform motion on global frequency-domain aerodynamic loads generated by the VAWT on a floating support structure.

Chowdhury et al. (2016) carried out numerical validation of an experimental work of VAWT in upright and tilted conditions for applications like Floating Axis Wind Turbine. The numerical validation was accomplished by CFD analysis by solving Unsteady Reynolds Averaged Navier-Stokes (URANS) equation.

#### ***Floating wind turbine under abnormal loads***

Special load conditions for offshore wind turbines are earthquakes, icing or component faults. These special load conditions are well defined in the load case tables from the ICE 61400-3 standard or in the DNV-GL guidelines.

Jiang et al. (2015) presented a comparative study of shutdown procedures on the dynamic responses of wind turbines which may induces excessive loads on the support structure. The short-term extreme response and the annual fatigue damage to the structural components were compared under normal and parked condition. The procedure of three blade shutdown is recommended for both the turbine cases because one or two blade shutdown with grid loss may results in a significant rotor over speed. Etemaddar et al. (2016) performed response analysis of spar-type FOWT under blade pitch controller faults, and made comparison with an onshore wind turbine, using the OC3-Hywind model.

Bae et al. (2017) performed numerical simulations of the performance of a floating offshore wind turbine (FOWT) with broken mooring line. An aero-hydro-servo-elastic-mooring coupled dynamic analysis in the time domain is performed for the simulation. It is observed that due to loss of one mooring line, the orientation of the platform and turbine can be changed which leads to large error in the nacelle yaw motion and affects the FOWT negatively.

The fuzzy-based damage detection method for TLP and Spar floating wind turbines was performed by Jamalkia et al. (2016) for the dynamic response of the structure. The variation values of the mean amplitude of dynamic response and frequency characteristics of the structure due to stiffness changes of mooring lines are considered as input parameters to the fuzzy system.

### 2.3 *Physical testing*

In the last few years, there is an increasing research interest in physical testing including lab testing of offshore wind turbines and in particular floating wind turbines. Today's wind turbines are designed using first principles and the external loads and structural responses are explicitly calculated typically using time-domain numerical codes. Validation of such codes against measurements from lab tests under controlled and usually easily-known environmental conditions is an important part of the recent research work. However, there are a number of challenges in lab testing of offshore wind turbines (Muller et al., 2014):

- Quality of wind field generation in ocean basin or towing tank
- Conflicts in the scaling laws for aerodynamics (Reynolds scaling) and hydrodynamics (Froude scaling) and therefore how to match both mean and dynamic wind turbine aerodynamic loads for a wide range of wind speeds
- Simulation of wind turbine faults in model tests
- Consideration of structural flexibility

The recently-developed real-time hybrid testing technique (Azcona et al., 2014; Chabaud, 2016; Kanner, 2015) which combines physical testing with numerical simulations solves some of the problems mentioned above.

Field measurements of prototype offshore wind turbines are always useful since there are no scaling problems. However, the main challenge is the uncertainties in the measurements. From the validation of numerical codes point of view, both environmental conditions (here mainly wind and waves) and wind turbine responses must be simultaneously and accurately measured. Measurement of wind speed at the rotor swept area is particularly challenging and there are ongoing research projects, developing for example LIDAR systems. Moreover, prototype testing at sea is costly and the measurement data are often not publically available.

In this section, we will mainly discuss the recent work on lab testing of offshore wind turbines. Wind tunnel tests for rotor aerodynamic design and tests of mechanical components (such as drivetrains) are excluded because of less relevance for ISSC. Moreover, we focus on dynamic behavior tests of offshore wind turbines in wind and waves, rather than ultimate or fatigue strength tests of wind turbine blades or other structural components.

#### 2.3.1 *Lab testing*

##### ***Bottom-fixed wind turbines***

Offshore wind turbines with a bottom-fixed foundation (such as monopile, tripod, jacket or GBS) have been well developed and widely used in the industry. But, the development of large-scale (8-10MW) wind turbines in larger water depths (40-60m) leads to large-diameter monopile design and therefore hydrodynamic loads become more important. The recent experimental work on bottom-fixed foundations are related to nonlinear wave loads on monopile and jacket, foundation-soil interaction and seismic loads and responses.

Suja-Thauvin et al. (2017) presented the experimental results from MARIN on a monopile foundation (at 1:30.6 scale) considering a fully flexible model in which the first and second eigen-frequencies are properly scaled. Both breaking and nonbreaking waves are considered. It is found (as shown in Figure 2.9) that in addition to the quasi-static responses due to the first-order wave loads and the ringing responses of the first eigen-mode, the resonant responses of the second eigen-mode are excited by the breaking wave loads. The corresponding contributions to the largest response are about 40-50%, 30-40% and 20%, respectively.

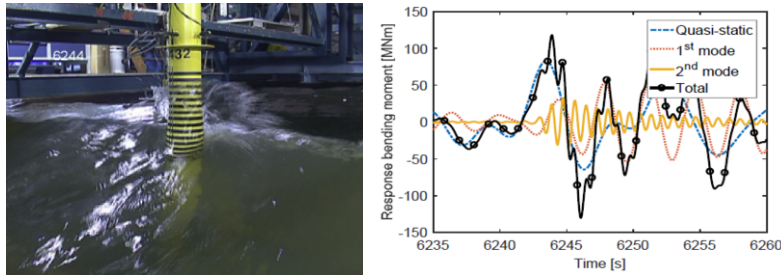


Figure 2.9: The flexible monopile model tested in MARIN (left) and examples of the bending moment response time series at the bottom (right) (Suja-Thauvin et al., 2017)

An extensive experimental campaign (Bachynski et al., 2017) on a 1:48 scale monopile was carried out at SINTEF OCEAN (previously MARINTEK) for Statoil in connection with the development of the Dudgeon wind farm in UK, as shown in Figure 2.10 (left picture). The focus was on the nonlinear wave loads and ringing-type resonant responses in nonbreaking extreme waves. The comparison with the experimental results indicates that numerical methods using a beam element model with a modified Morison wave load model and second-order wave kinematics gave reasonable prediction of the ringing responses of the fully flexible model. In addition, the results from three monopile models (including a rigid, a rigid with an equivalent rotational spring at bottom and a fully flexible model) are compared and the rigid model with rotational spring behaves similarly as the fully flexible model.

Loukogeorgaki et al. (2016) performed a model test of wave slamming loads on a three-legged jacket foundation (at 1:18 scale) for offshore wind turbines in the CNR-INSEAN wave tank in Italy, as shown in Figure 2.10 (right picture). The load components at the bottom of the jacket were measured. Their experiments for the focused wave cases revealed that there exists an additional impact on the leeward jacket legs slightly after the first impact on the windward leg. This induces complex dynamic responses of the complete structure.

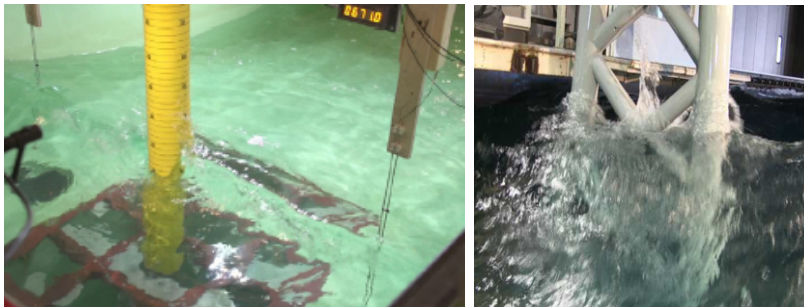


Figure 2.10: The monopile model tested in SINTEF OCEAN (left) (Bachynski et al., 2017) and the jacket model tested in CNR-INSEAN (right) (Loukogeorgaki et al., 2016)

Soil-structure interaction is a traditional research topic for bottom-fixed wind turbines. In particular, a proper modelling of the soil resistance in terms of both nonlinear and time-dependent spring and damping effects on the dynamic responses of the bottom-fixed wind turbines is very important. Randomness in soil property at the offshore wind farm sites is another challenge. Therefore, lab tests or field tests are developed to validate numerical models.

An interesting field test of a monopile foundation under excitation of an eccentric-mass shaker was carried out by Versteijlen et al. (2017) to investigate the lateral dynamic soil-stiffness in real conditions. The measured response of the monopile is used to validate an effective 1D stiffness method and the current employed p-y stiffness method for small strain conditions. The results show that the effective stiffness method seems to overestimate the actual low-frequency stiffness while the p-y method will significantly underestimate it. In addition, a damping ratio of 20% for the monopile only (equivalent to 0.14% for the full structure) was identified from the field test.

Besides normal monopile foundations, suction buckets are recently developed for offshore wind turbines. In the work done by Foglia et al. (2015), thirteen monotonic and cyclic lab tests on a skirted footing bucket model (with a diameter of 0.3m and an embedment ratio of 1) were carried out to study the drained behavior of the soil considering the typical loading conditions with large overturning moment and horizontal force for an offshore wind turbine. The test results were used to validate a complete macro-element approach for both monotonic and cyclic loadings. A large-scale model test on a novel hybrid bucket foundation (with a diameter of 3.5m and a height of 0.9m) for offshore wind turbines has been performed by Ding et al. (2015), in which the horizontal load-displacement curve and the horizontal bearing capacity of the bucket in saturated clay were determined by tests. A numerical model based on finite element method for predicting the load-displacement curve was validated against the test results.

Besides wind and wave loads on bottom-fixed wind turbines, earthquake loads is another important design consideration for some geographical areas. Zheng et al. (2015) performed a test of a scaled (1:30) monopile wind turbine under joint earthquake and wave loads, with focus on the nacelle acceleration response, in the towing tank equipped with a shake table at Dalian University of Technology. They found that it is important to consider wave loads simultaneously when predicting the dynamic responses under earthquake loads. In the same lab, Wang et al. (2016c) performed a similar test on a bottom-fixed penta-pod wind turbine at a scale ratio of 1:30. The numerical FE simulations using the measured acceleration at the shake table as input predict quite accurate responses of the complete structure under seismic loads.

### ***Floating wind turbines***

Model testing of floating wind turbines in hydrodynamic labs became one of the hot research topics in recent years. Some of these studies focus on the effect of nonlinear hydrodynamic loads on the motion responses of floating wind turbines. In Simos et al. (2018), the wave-induced slow-drift motions of a three-column semi-submersible wind turbine were studied experimentally and numerically. The comparisons against the experimental results indicate that the full QTF model gives better predictions of the slow-drift motions than the Newman's approximation, which underestimates the second-order responses. In the study carried out by Pegalajar-Jurado et al. (2017) on the motion responses of a TLP wind turbine, different nonlinear wave kinematics were applied, including the second-order wave kinematics, the fully nonlinear wave kinematics and the linear waves with an extrapolation of the wave kinematics up to the instantaneous wave surface. It was found that the numerical models based on the Morison's formula considering nonlinear wave kinematics predict the motion responses better than the pure linear wave model.

In model tests, hydrodynamic loads on floaters are typically scaled according to the Froude law and then the main challenges are related to the modelling of wind turbines and the scaling of aerodynamic loads. The scaling issue has been thoroughly studied by Make & Vaz (2015) in which they investigated the flow over two (floating) wind turbines using RANS CFD calculations at model and full-scale Reynolds numbers conditions. The NREL 5MW and MARIN Stock Wind Turbine (which was designed to have the same thrust at model scale as the NREL turbine at full scale) were considered. Good agreement between the CFD and the ex-

perimental results was obtained for the model-scale turbine for the thrust coefficient, but not the power coefficient. The large Reynolds effects on the flow passing these two turbines are shown and explained.

Muller et al. (2014) and Stewart & Muskulus (2016) summarize the different experimental practices for modelling of wind turbines in labs. It includes the passive methods (concentrated masses with added point forces, over drag disks with a rotating body), the physical turbine methods (geometrically-scaled but pitch angle-redistributed rotor blades, redesigned performance-match rotor blades) and the hybrid methods (controlled duct fan to simulate thrust force only, other actuators (for example multiple hydraulic actuators) to simulate integrated wind turbine loads in multiple degrees of freedoms).

In the previous ISSC report (Gao et al., 2015), we discussed some of these methods and in this report, we will mainly review the new experimental techniques developed in recent years. This includes:

- Physical turbine model testing method
- Real-time hybrid model testing method

- ***Physical turbine model testing method***

To reproduce the equivalent thrust force is the first step in model testing of floating wind turbines, for which the thrust-induced pitch moment is the most important aerodynamic load effect with respect to motion responses of floating wind turbines. In recent years, attempts have been made to improve the reproduction of both mean and dynamic thrust force for a wider range of wind speeds, in particular by active blade pitch control at model scale.

Huijs et al. (2014) reported the results of the model tests for the GustoMSC Tri-Floater semi-submersible wind turbine concept at a scale ratio of 1:50 at MARIN (as shown in Figure 2.11) using the NREL 5MW wind turbine, in which both Froude-scaled thrust force and active blade pitch control at model scale were realized. Their study indicates that a Froude-scaled model with active blade pitch control is feasible and can significantly improve the mean thrust force reproduction in tests for typical operational conditions, while such model still cannot represent the dynamic responses of the turbine in full scale.

In another study by Goupee et al. (2017) at MARIN, the influence of different blade pitch and generator controls on the global responses of the DeepCwind-OC5 semi-submersible floating wind turbine was investigated experimentally for a model at 1:50 scale with the NREL 5MW turbine, as shown in Figure 2.11. This includes a fixed blade pitch with a constant rotor speed (no control), a collective blade pitch integral control with a constant rotor speed, and a variable speed generator control. The active blade controls with a Froude-scaled performance-matched wind turbine can reproduce the general trends of the motions one would observe for a full-scaled floating turbine.

Hara et al. (2017) discussed the model-based design of a blade pitch controller for a FOWT scale model. A linear state-space model of the FOWT scale model was created by using system identification, and the linear model was used to design a blade pitch controller.

Duan et al. (2017b) conducted the model tests of the OC3 spar floating wind turbine using both a thrust-matched blade-redesigned rotor and a geometrically-scaled rotor at 1:50 scale in the Ocean Basin at Shanghai Jiao Tong University, as shown in Figure 2.11. The study revealed the significant differences in the motion responses and the tower bending moments of the spar concept using two different model-scale rotors. This suggests the unsuitability of the geometrically-scaled rotor for model testing.

In the ongoing EU INNWIND project, a series of model test campaigns have been carried out on floating wind turbine concepts (a TLP (Pegalajar Jurado et al., 2016)), the scaled OC4

semi-submersible (Koch et al., 2016) and the Triple-Spar semi-submersible (Bredmose et al., 2017)), all supporting a 1:60 scale DTU 10MW wind turbine. The TLP test was carried out in the wave tank at DHI, Denmark, while the two semi-submersible tests were performed in the ocean basin of ECN, France (as shown in Figure 2.11). A performance-matched redesigned rotor was considered and active blade pitch control was applied. The design of the real-time blade pitch control system for model testing was detailed in Bredmose et al. (2017). Numerical simulations using FLEX5 were conducted and compared with the test results for the TLP concept (Pegalajar Jurado et al., 2016). It is found that FLEX5 gives good predictions of the surge motion and the mooring line tension, while it does not predict the pitch resonant motions reasonably well for the wave only cases. In the study of the scaled OC4 semi-submersible (Koch et al., 2016), the validation of a SIMPACK numerical model against the test results was performed. Moreover, the test data will be made publically available for future research work on floating wind turbines.

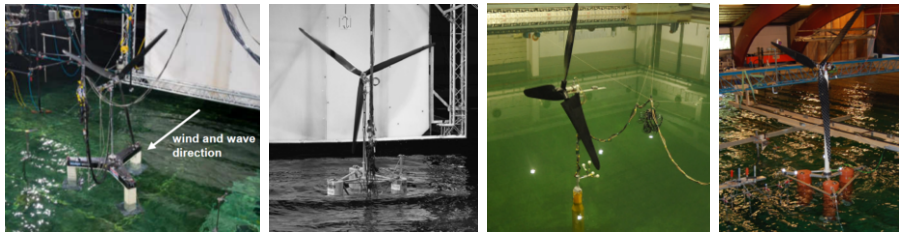


Figure 2.11: Floating wind turbine models tested at different hydrodynamic labs (from left: GustoMSC Tri-Floater at MARIN (Huijs et al., 2014); DeepCwind-OC5 semi-submersible at MARIN (Goupee et al., 2017); OC3 spar at SJTU (Duan et al., 2017a); Triple-Spar semi-submersible at ECN (Bredmose et al., 2017))

#### • *Real-time hybrid model testing method*

One of the major developments in the last few years in experimental techniques for floating wind turbines are the real-time hybrid model testing methods (Azcona et al., 2014; Chabaud, 2016; Kanner, 2015). The basic idea of the hybrid testing is to combine physical experiments with numerical simulations, as shown in Figure 2.12 by Sauder et al. (2016) for testing a braceless semi-submersible floating wind turbine. The physics of the waves, current and their induced hydrodynamic loads and responses of the semi-submersible floater are realized, while the aerodynamic loads on the wind turbine in a turbulent wind field are numerically simulated and applied through actuators on the test model in real time. This method avoids the scaling issue of aerodynamic loads in a hydrodynamic lab test and allows us to study the coupling effect of the wind, wave and current induced loads and responses of floating wind turbines (Hall et al., 2017). It also opens the opportunities to study complex loading conditions that are required by design rules, such as wind turbine fault conditions, start-up and shut-down events.

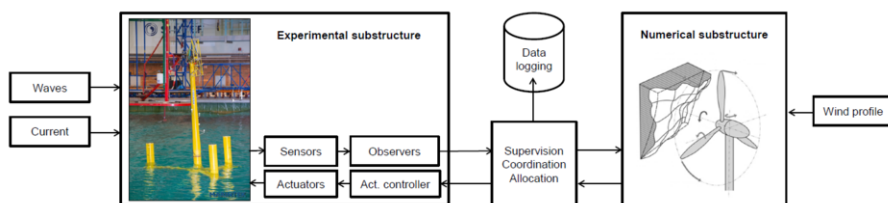


Figure 2.12: The methodology of real-time hybrid model testing for offshore wind turbines (Sauder et al., 2016)



The basic assumption is that the numerical simulation part (wind field generation and wind turbine aerodynamics in this case) typically using a numerical code should be already validated and correct. Such validation can be carried out by wind tunnel tests or field measurements of onland and offshore wind farms. The numerical code should be fast enough to calculate the demanded loads based on the motion measurements of the floating wind turbine in the lab test. The actuators should respond quickly to apply the demanded loads in real time or any delay in the actuation system should be compensated for in the actuator controller design. In Sauder et al. (2016), the frequency limit for actuators was set to achieve a quick response to the wave-induced motions of the floater since the total integrated wind loads are of concern as shown in Figure 2.13. Moreover, the eigen-frequency of the actuation system needs to be designed away from any frequency of interest in wind and wave excitations. For bottom-fixed wind turbines, the feasibility of such experimental technique to capture the high-frequency resonant responses of the first bending mode needs to be investigated.

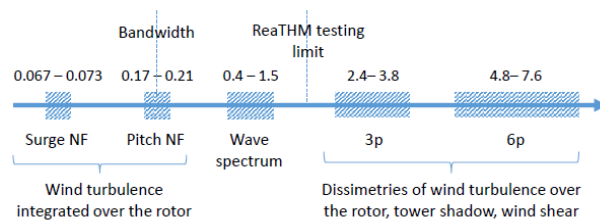


Figure 2.13: Frequency map for real-time hybrid model testing of floating wind turbines (Frequency values are in Hz, model scale. p denotes the rotational speed of the rotor. NF denotes natural frequency) (Sauder et al., 2016)

The developed real-time hybrid model testing method (Chabaud, 2016) was applied to test a braceless semi-submersible 5MW NREL wind turbine at 1:30 scale in the Ocean Basin at SINTEF OCEAN through the research centre NOWITECH (Sauder et al., 2016; Bachynski et al., 2016; Berthelsen et al., 2016). Six actuators with pulleys via thin lines connected to the frame on the semi-submersible were used to produce the integrated wind turbine loads in 5 DOFs (except the vertical force, which is shown to be less important for motion responses (Bachynski et al., 2015)). A detailed verification of the actuators and the calibration of a numerical model were carried out through the basic test cases (decay, wind-only and regular wave tests). The test results were then used to validate numerical models for conditions with irregular waves and turbulent wind, with focus on motion responses (Karimirad et al., 2017) and cross-sectional loads in the floater (Luan et al., 2017). Karimirad et al. (2017) obtained a good agreement between the numerical simulations and the experimental measurements of pitch motion responses and also demonstrated the limited effect of second-order wave orders for this braceless semi-submersible wind turbine, as shown in Figure 2.14.

A simpler real-time hybrid testing method was presented by Azcona et al. (2014), in which they used a ducted fan at the nacelle position of a semi-submersible floating wind turbine to provide the variable desired thrust force based on the numerical simulations, as shown in Figure 2.15. A 6MW wind turbine model was tested at a scale ratio of 1:40 at ECN, France. A good agreement between the experimental results of the platform motions and the recalculations from the numerical code FAST was obtained, showing the validity of this experimental technique.

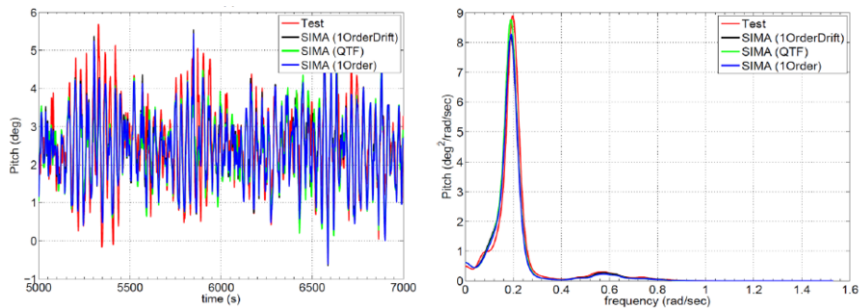


Figure 2.14: Comparison of the time series (left) and spectra (right) of pitch motions obtained by simulations (SIMA) and experiments (Test) ( $U_w=25\text{m/s}$ ,  $H_s=5.9\text{m}$ ,  $T_p=11.3\text{s}$ ) (Karimirad et al., 2017)

Kanner (2015) developed a hybrid testing method, called the Multiple Integrated and Synchronized Turbines, to test a semi-submersible floater at 1:82 scale with two counter-rotating vertical-axis wind turbines (VAWTs), as shown in Figure 2.15. The two synchronized counter-rotating turbines can produce zero net yaw moment on the floater. The test was carried out at the UC Berkeley Physical-Model Testing Facility. The aerodynamic loads on two VAWTs were calculated using high-order, implicit, large-eddy simulation and applied through two pairs of spinning, controllable actuators (fans) in the model test. The developed time-domain numerical simulation tool is able to confirm some of the experimental findings, taking into account the decoupled properties of the slow-drift hydrodynamics and wind turbine aerodynamics.

Alternatively, hybrid testing methods are also developed for wind tunnel tests of floating wind turbines (Bayati et al., 2016; Giberti & Ferrari, 2015), in which the floater motions are imposed by a movable foundation and the wind field and the wind loads are generated physically. Such methods were developed in the wind tunnel at the Polytechnic University of Milan for the study about the effect of surge and pitch motions on the aerodynamics of the 1:75 scale DTU 10MW wind turbine using a 2DOF test rig (Bayati et al., 2016), as shown in Figure 2.15. The tests with platform surge and pitch motions at both a low and wave frequency and up to rated conditions were conducted. The results show hysteretic behaviours in the force-velocity plots, always of dissipative nature. They are now developing a 6DOF robotic platform for testing floating wind turbines (Bayati et al., 2014).

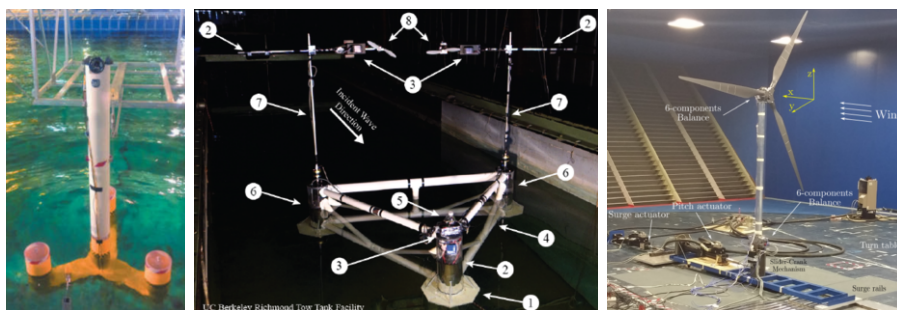


Figure 2.15: Other examples of hybrid testing of floating wind turbines (from left: semi-submersible wind turbine with a ducted fan (Azcona et al., 2014); counter-rotating vertical axis wind turbine with controllable fans (Kanner, 2015); wind tunnel testing with a movable foundation (Bayati et al., 2016))

2.3.2 Field testing

Bottom-fixed wind turbine technology is relatively mature. However, there is a need for testing of large-scale wind turbines and validation of the numerical codes for such turbines. There exists an extensive field measurement campaign (called RAVE) with research purposes at Alpha Ventus wind farm in Germany, see Muller & Cheng (2016), Muller et al. (2016), Lott & Cheng (2017).

Guzman & Cheng (2016) reported a comprehensive comparison of the measured and simulated structural responses of a tripod AD5-116 5MW wind turbine (NO.7 turbine in as shown Figure 2.16) considering 13 months of data. The bending moments in tower and at blade root were compared in detail. The numerical simulations were carried out in the coupled Flex5-Poseidon tool (Kaufer et al., 2009) using simulated (rather than measured) wind and wave conditions. However, in the simulations, similar turbulence intensity factor and significant wave height/spectral peak period for a given mean wind speed were considered and response statistics were compared, as shown in Figure 2.17. The 10-minute extreme values of the tower fore-aft bending moment, including both the mean and the ranges of predictions, agree very well with the measurements for different mean wind speed. Figure 2.17 also shows the comparison of the fatigue damage equivalent loads (DEL) of the blade flap-wise bending moment. The numerical tool predicts a good general trend, but less scatter of the blade responses for the mean wind speed close to the rated value.

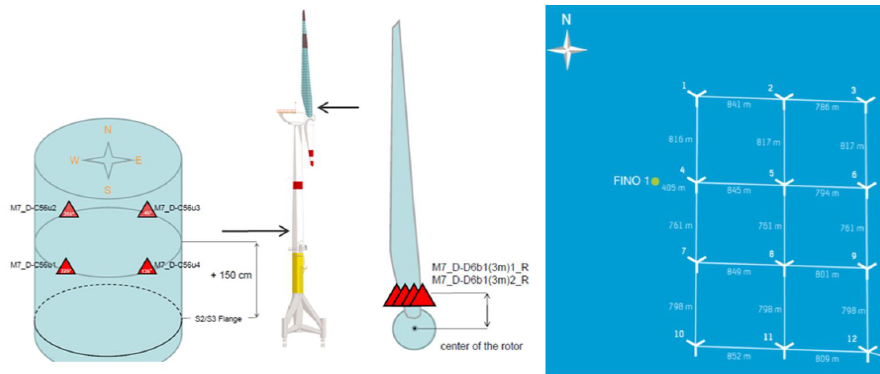


Figure 2.16: Illustration of the tripod wind turbine, its measurements and the Alpha Ventus wind farm configuration (Guzman & Cheng, 2016)

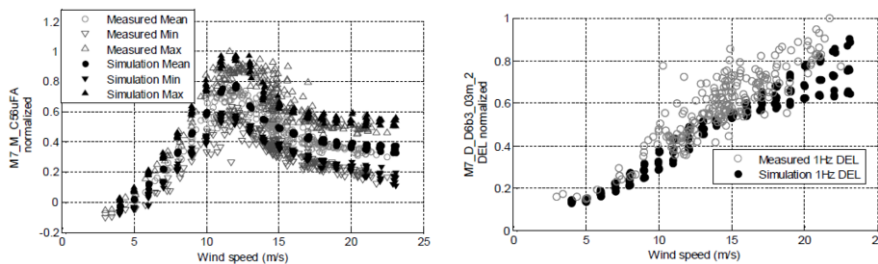


Figure 2.17: Comparison of the 10-minute extreme responses of the tower fore-aft bending moment (left) and the damage equivalent loads (DEL) of the blade flap-wise bending moment (right) (Guzman & Cheng, 2016)

As for floating wind turbines, there are quite a few prototypes that were tested and are under testing in Norway, Portugal, Japan and US. The WindFloat prototype with a 2MW Vestas

turbine was tested in Portugal since 2011 and decommissioned in 2016 (Principle Power, 2017). A complete lifecycle of development (from design, fabrication, installation, operation/maintenance and decommissioning) was successfully demonstrated. Similarly, the VoltturnUS 1:8 prototype with 20kW turbine was tested in US for 18 months between 2013 and 2014 (Viselli et al., 2015).

As discussed in the last ISSC report (Gao et al., 2015), lack of publically-available full-scale field measurements was and remains a general problem for the research community in the area of offshore wind turbines and in particular, floating wind turbines. The subject of floating wind turbines attract a significant number of researchers in recent years to develop numerical codes and experimental techniques. There are very limited publications on validation of numerical simulations against field measurements, although several prototypes of floating wind turbines exist. This might be because most of these prototypes are developed by companies with the aim for commercialization. Besides the competition between the turbine manufacturers that already exist in the market for onshore and offshore bottom-fixed wind turbines, the floating wind turbine market could also become a very competitive market with regards to the foundation technology. In the ongoing OC5 benchmark study, the data from lab tests were used for validation of a variety of numerical codes and it is also planned to compare simulations against the measurement data from a bottom-fixed wind turbine farm. In their future work, using the measurements from an existing prototype of floating wind turbines could be considered and would be beneficial for most of the code developers.

Nevertheless, validation of numerical simulations against field measurements were carried out for the Statoil Hywind Demo using a FAST model (Driscoll et al., 2016). The numerical simulations were carried out using reproduced wind speed time series from measurements and similar wave spectrum. The comparison shows that the wave-frequency motion responses for both low ( $H_s=1.4\text{m}$ ) and moderate ( $H_s=4\text{m}$ ) seas can be accurately predicted by the numerical model. However, the low-frequency roll responses and the yaw responses do not agree well with the measurements, indicating a need for a more advanced mooring line model (rather than a linear yaw stiffness model) and a model with short-crested waves.

#### ***2.4 Transport, installation, operation and maintenance***

In order to reduce the cost of offshore wind farms, it is important to look at marine operations related to different phases of offshore project, including transport, installation, operation, maintenance and decommissioning. In view of the significant development plan, the offshore wind industry is an area where the ship and offshore technology community like ISSC should and can contribute. In particular, there is a need to develop purpose-built installation vessels, accommodation vessels, Service Operation Vessels (SOVs) and Crew Transfer Vessels (CTVs) (Turner, 2012). Moreover, the existing jack-up installation vessels have to be upgraded in terms of crane capacity and leg length in order to meet the market needs with increasing turbine size and water depth (MAKE Consulting, 2016). Since a commercial offshore wind farm normally consists of 50-100 turbines, logistics planning becomes very important for such installation and maintenance activities (Barlow et al., 2017; Vis & Ursavas, 2016; Dalgic et al., 2015). In this report, we will focus more on offshore wind installation and less on maintenance activities.

##### ***2.4.1 Transport and installation***

Although tripod, jacket, GBS and even floating foundations have been developed and used to support wind turbines, bottom-fixed monopile wind turbines are still the majority in today's offshore wind farms. The transport and installation methods strongly depend on the type of foundations (Asgharpour, 2016). Monopile, tripod and jacket wind turbines are normally transported by barges and installed component-by-component at the offshore site. Large floating crane vessels have been used to install foundations, but wind turbine blades, nacelle and tow-

er are typically installed using jack-up vessels due to the high precision required in the mating operation of the blades into the hub, as shown in Figure 2.18 for one of the largest offshore wind farms in Europe under construction.

US installed their first offshore wind farm at the Block Island site in 2016 (Clean Technica, 2016), which consists of five 6MW wind turbines, as shown in Figure 2.18. Fred. Olsen Windcarrier did the offshore installation. The substructure foundation includes lower jacket and upper transition deck sections to reduce the weight of the assembly lifts, which was considered necessary to utilize the available assembly systems and vessels with limited lift capacity. ISO standards and design loads from IEC 61400-3 (2009) and API Recommend Practice 2A-WSD (2014) were employed with consideration of robustness levels of ultimate strength for Atlantic hurricane winds (Finucane & Hall, 2016).

The world's first small-scale farm of floating wind turbines was commissioned in Scotland in late 2017 based on the Hywind technology from Statoil, Norway. It consists of five 6MW Siemens turbines. Turbine blades, nacelles and towers are pre-assembled onshore before they are installed by one of the largest floating crane vessel, semi-submersible SAIPEM 7000, onto the spar floaters in the fjord in Norway, see Figure 2.18. Then, they are wet-towed to offshore Scotland and hooked up with mooring systems. A similar process using a large floating crane was adopted in the installation of the downwind 2MW hybrid spar wind turbine in 2013 in Japan (Utsunomiya et al., 2015). However, when developing commercial wind farms, the cost should be further reduced and new installation methods which rely less on expensive large crane vessels are preferred. In that respect, semi-submersible floating wind turbines have the advantage of being pre-assembled in one piece in the shipyard and towed to the offshore deployment site, as the WindFloat prototype project did (Principle Power, 2012). They also demonstrated the decommissioning process in 2016, disconnecting power cables/mooring lines as well as decommissioning the turbine at Sines quay side in Portugal (Principle Power, 2017; Roddier et al., 2017), see Figure 2.18.



Figure 2.18: Examples of offshore wind farms during installation (from left: Gemini Wind Farm in the Netherland, installed by Van Oord (Irving, 2017); Block Island Wind Farm in the US, installed by Fred. Olsen Windcarrier (Finucane & Hall, 2016); Statoil Hywind Wind Farm in Scotland, during assembly in Norway by SAIPEM 7000 (Statoil, 2017b); WindFloat prototype at Sines quay side in Portugal, under decommissioning (Roddier et al., 2017))

Different installation vessels were reviewed by Paterson et al. (2017), with focus on the vessels that performed the tasks in UK Offshore Wind Round 1 and Round 2, and Ahn et al. (2016), considering other vessels that were used in offshore wind farms in Europe. Paterson et al. (2017) also demonstrated a probabilistic simulation tool for optimal selection of vessel fleet, while Ahn et al. (2016) focused on the best installation method for a Korea offshore site.

One of the main challenges in the installation phase is to increase the weather window and to avoid any unexpected delays. This requires a good understanding of the performance of the installation vessels in waves. Therefore, numerical methods and models have been developed to estimate systems' dynamic responses during installation. Most of the studies focused on

static (Collu et al., 2014) or steady-state dynamic responses (Li et al., 2016), while in a few studies, the nonstationary features of the installation process are considered (Li et al., 2015). Li (2016) developed a numerical method for analyzing the dynamic responses of the monopile when it is lowered from the air into the water, considering the submergence-dependent hydrodynamic loads on the monopile and the vessel shielding effect. Regarding wind turbine blade installation, a numerical tool was developed by Zhao et al. (2017) to simulate the blade rigid-body motion responses in turbulent wind conditions using either jack-up or floating installation vessels.

There exist few model tests for complex marine operations in hydrodynamic labs and experimental techniques have not been extensively developed for assessment of the feasibility and safety of marine operations. The challenge is to scale both hydrodynamic loads and mechanical components and to simulate the actual operational phases involving transient hydrodynamic loads and structural responses. However, this is certainly an interesting area to develop and it will be very useful for validation of novel concepts for marine operations, for example installation of floating wind turbines (Hatledal et al., 2017).

For any marine operation, there exists one or multiple operational limits due to the safety requirements (e.g. personnel and property safety) which are often expressed as sea state limits. Most of wind turbine installation operations can be only performed in benign sea states (for example with  $H_s$  in order of 1-3 m), depending on vessels and tasks. Detailed information about the limiting environmental conditions for different construction vessels can be found in Table 2.2 (Ahn et al., 2017).

Such environmental limits should be established preferably using response-based criteria, but currently they are based on industrial experiences. A generic methodology for assessment of the operational limits and operability of marine operations was proposed (Guachamin-Acero et al., 2016; Guachamin-Acero, 2016). The basic idea is to estimate structural dynamic responses during operations in all possible sea states using numerical models and then backwards derive the limiting environmental conditions that will lead to the allowable response level. This methodology was applied to monopile foundation installation (Li et al., 2016) and transition piece installation (Guachamin-Acero et al., 2017a). A similar approach, called reliability-based decision support model, was developed by Gintautas et al. (2016), in which response statistics of the installation equipment were obtained based on simulations and used to estimate the weather windows in combination with the ensemble weather forecast model.

Table 2.2: Limiting environmental conditions for construction vessels (Ahn et al., 2017)

Vessel type	Operating equipment	Capacity	Transit condition		Operating condition	
			Speed (knots)	Wave height ( $H_s$ , m)	Wave height ( $H_s$ , m)	Wind speed (m/s)
WTIV	Jack up/down + crane	Crane capacity: 800–1500 ton	12	3.0	2.5	16
Jack-up barge	Jack up/down + crane	Crane capacity: 800 ton	4	2.5	1.65	16
Crane barge	Shear crane	Crane capacity: 3000 ton	4	1.5	1.0	10
Cargo barge	Stacking (without crane)	2000-5,000p	4	1.5	1.5	14
Tug boat	Towing	750 hp, 1000 p	13	2.5	1.0-1.65	14

One of the principles to reduce the installation cost is to reduce the number of operations (in particular crane operations) at the offshore site. Therefore, many novel installation methods or concepts were developed considering a pre-assembled rotor-nacelle-tower structure. Guacha-

min-Acero et al. (2017b) developed an installation concept for small crane vessels using the inverted pendulum principle in which the pre-assembled rotor, nacelle and tower can be installed via rotation through a rotating frame at the tower base. In the research centre SFI MOVE at NTNU, Hatledal et al. (2017) developed a catamaran installation vessel concept which can carry 3-4 pre-assembled rotor, nacelle and tower and install them on top of a monopile or a spar foundation through its onboard lifting mechanism. This is a similar concept as Ulstein's Windlifter concept (Ulstein, 2017).

Moreover, some foundation concepts, such as GBS (Esteban et al., 2015), allow the onsite installation with one completely pre-assembled structure. Zhang et al. (2016) developed a hybrid suction bucket foundation with seven compartments for offshore wind turbines. The sinking of the foundation with a complete wind turbine installed on it is realized by depressurizing the compartments and the verticality of the foundation is achieved by adjusting the pressures in different compartments. A model test at 1:10 scale was performed to demonstrate the feasibility of this technology.

#### *2.4.2 Operation and maintenance*

There is a wide range of topics related to offshore wind turbine operation and maintenance (O&M) of interest. However, in this report, we will only give a short discussion. It is suggested that the V.4 committee for the next term work more on this topic, probably together with the committees that deal with structural health monitoring for marine structures in general since there are many common challenges.

Condition monitoring and structural health monitoring of offshore wind turbine components (such as gearbox, blade, tower and foundation) has become a hot topic for research (Yang, 2016; Wymore et al., 2015; Romero et al., 2017; Mieloszyk & Ostachowicz, 2017). This is in line with the increased use of sensors, SCADA (Supervisory Control and Data Acquisition)-based and purpose-designed condition monitoring systems for commercial offshore wind farms. One of the main purposes of such system is to detect degradations or damages in wind turbine components in an early stage to prevent them from developing into component or system failures. Therefore, different condition monitoring techniques and signal processing methods have been used for fault detection in wind turbine components (Martinez-Luengo et al., 2016).

From marine operations point of view, the access systems for maintenance and repair are of concern. In particular, crew and equipment transfer are the most important operations for scheduled and emergency maintenance and repair work for offshore wind turbines. On one hand, increasing the reliability of wind turbine components is one of the crucial aspects for offshore wind projects. On the other hand, high accessibility in most of the sea conditions becomes very important to reduce the downtime caused by component failure and shutdown of the wind turbines. A review of the existing offshore wind access systems was carried out by Katsouris & Savenije (2017), including crew transfer vessels (CTVs) with a conventional method of access to the boat landing and recently developed service operation vessels (SOVs) equipped with motion compensated gangways. They also found that CTVs can typically provide access up to sea states of  $H_s$  of 1.5-2 m, while SOVs with motion compensation could be operated up to sea states of  $H_s$  of 3 m. In addition, helicopter support can be very beneficial due to fast response time and almost unlimited accessibility. Guaniche et al. (2016) presented a methodology to assess limiting wave heights for safe personnel transfer between different service vessels and a floating wind turbine. The vessel and the floating wind turbine platform were modelled as a rigid, constrained multibody hydrodynamic model in the frequency domain.

Similar to installation, logistics planning for offshore wind farm operation and maintenance activities is also very important and many studies have been performed to optimize the fleet

selection for such activities at the wind farm level (Halvorsen-Weare et al., 2013; Sperstad et al., 2017). O&M simulation tools have been developed to (Katsouris & Savenije, 2017) estimate the maintenance cost for a selection of O&M fleet and the wind farm availability. Such tools are also used to find the most cost-effective O&M and logistics strategy. In particular, an advanced logistics planning tool was developed by Dalgic et al. (2015) using a time-domain Monte-Carlo simulation approach which takes into account environmental conditions, operability of transportation systems, component failure type and frequency, and simulation of repairs.

### **2.5 Design standards and guidelines**

In the last ISSC report (Gao et al., 2015), the existing design standards and guidelines were discussed. In this report, the discussion will focus on the updates in recent years.

The IEC 61400 set of standards are the commonly used standards in the wind and offshore wind industry in particular in Europe. The current version of the IEC61400-3 (IEC, 2009) standard considers only bottom-fixed offshore wind turbines and a revision will be published in 2018. Accordingly, a technical specification of IEC 61400-3-2 for floating wind turbines will also be published in 2018.

Additional standards from API, ISO, and guidelines from classification societies such as DNV-GL, ABS, BV, are also considered essential to address key aspects in the development, deployment and operation of offshore wind projects.

These standards and guidelines address many key project aspects, including safety; site condition assessment; design evaluation of wind turbines, blades and support structures; manufacturing; transportation; installation, commissioning and certification; and operation. Sirmivas et al. (2014) made a thorough review of these standards and guidelines and assessed the major differences between them.

DNVGL-ST-0126 (DNV-GL, 2016) is a fully updated version of the standard for onshore and offshore wind turbine support structures, which was developed based on long experience in DNV-GL. This standard is applicable to bottom-fixed wind turbines and covers design of steel and concrete towers, gravity-based concrete foundations and steel foundations such as monopile, jacket structures and suction buckets. DNV-OS-J103 (2013) is an early version of the DNV-GL offshore standard for design of floating wind turbines. A new version of the standard, DNVGL-ST-0119, will be released during 2018. DNV-GL (2017a) is now running a JIP with focus on specifications for coupled analysis of floating wind turbines using numerical tools and experimental methods. The outcome of this JIP will be a Recommendation Practice, named DNVGL-RP-0286, Coupled Analysis of Floating Wind Turbines.

ABS published the revision of the Guides (ABS #176, 2015a; ABS #195, 2015b) in October, 2015. The two Guides provide the design, inspection, classification and certification requirements for bottom-fixed and floating offshore wind turbines. In particular, tropical cyclone conditions (such as hurricane and typhoon) are specified based on the measurements of tropical cyclone wind in the past 20 years. For bottom-fixed offshore wind turbines, a return period of 100 years was suggested for the design check. The Guidance Notes published in 2014 (ABS #206, 2014) provide suggested global performance analysis methodologies, modelling strategies and numerical simulation approaches for floating wind turbines.

Guidance Note NI 571 (2015), developed by BV, provides specific guidance and recommendations for the classification and certification of floating wind turbines. This Guidance Note is intended to cover floating platforms of different types (column-stabilized units, spar, TLP and barge) supporting single or multiple turbines with horizontal or vertical axis.

AWEA (American Wind Energy Association) published a recommended practice (AWEA, 2012) for bottom-fixed offshore wind turbines in the US waters (both state and federal), ad-



dressing all areas for offshore wind farm development, i.e. structural reliability, manufacturing, qualification testing, installation, construction, safety of equipment, operation and inspection, and decommissioning.

Up to now, although some guidelines exist, there still lacks detailed and specific rules or guidelines for offshore wind turbine transport, installation, operation & maintenance and decommissioning.

Most of the offshore wind turbines today are bottom-fixed wind turbines and they are installed mainly using jack-up vessels. LR (2014) developed a guidance note specific for offshore wind turbine installation vessels.

RenewableUK (2013) provided the second edition of Guidelines for the Selection and Operation of Jack-ups in the Marine Renewable Energy Industry in 2013. This guidance is intended to be relevant to all organizations contributing to the operation of jack-ups, but it is particularly relevant to jack-up owners/operators' technical staff and crews responsible for the operation of jack-ups, and to project managers in the marine renewable energy industry.

A standard DNVGL-ST-0054 (2017) is published to provide general safety principles, requirements and guidance for offshore wind power plants during transport, installation and decommissioning operations.

GL Garrad Hassan (2013) developed the Guide to UK Offshore Wind Operations and Maintenance to meet the need for standardized technical and commercial practices for offshore wind operation and maintenance.

## ***2.6 Comparative study of optimal offshore wind turbine support structure configurations in varying water depths***

This study aims to compare the weight (as an indicator for cost) of different configurations of support structures with respect to their deployment in different water depths. It is mainly carried out by the ISSC committee member, Dr. Athanasios Kolios, and his group from Cranfield University in UK. Two types of support structures, i.e. monopile and jacket, are considered in this study and an optimisation algorithm has been applied in order to compare concepts on a fair basis.

The response of the structure (based on FE analysis) for each case study under given loads is obtained through validated parametric models that have been developed for each case. The monopile consists of two parts, i.e. 1) monopile substructure, which is submerged into the water; and 2) monopile foundation, which is embedded into the soil. The soil profile considered in this study consists of three layers of sandy soil with given properties. In this study, the monopile support structure is modelled using beam elements. The soil-structure interaction is taken into account by modelling the soil using distributed springs, of which stiffness is derived from the p-y method defined in API standard. The springs are applied with 1m intervals along the monopile foundation in order to achieve good accuracy. Additionally, the RNA (Rotor-Nacelle Assembly) is treated as a point mass on the tower top. In this study, the transition piece is ignored for simplification. The parametric FEA model for OWT monopile support structures is used to calculate the natural frequencies of the NREL 5MW OWT on the OC3 monopile (Passon, 2006). The modal frequency results from the FEA model are compared against the results reported in Jonkman & Bir (2010), showing good agreement, with a maximum relative difference (1.55%) observed at 1st SS model. Comparison of deflection also show good agreement with a maximum relative difference (5.31%) observed for deflection of monopile foundation on mudline. This confirms the validity of the present FEA model of OWT monopile support structures.

The jacket structure model consists of mud-braces as well as several levels of legs and X-braces. The number of levels depends on the water depth. The RNA (Rotor-Nacelle Assem-

bly) is treated as a point mass on the tower top, and the transition piece is taken into account as a point mass attaching to the tower bottom. For simplification, the soil is not considered, and the bottom of the jacket is assumed to be fixed at the mudline. The parametric FEA model for OWT jacket support structures is used to calculate the natural frequencies of the NREL 5MW OWT on the OC4 jacket. The results from the FEA model show good agreement with those from Damiani et al. (2013), with a maximum relative difference (3.04%) observed at 2nd SS and FA modes. Similarly to the monopile, a comparison of deflections show good agreement with the results reported, with a maximum relative difference (8.23%) observed for deflection at RNA under load case 2. This confirms the validity of the present FEA model of OWT jacket support structures.

According to DNV-OS-J101 (DNV, 2014), the loads on OWT support structures can be categorized into eight groups, i.e. 1) wind loads; 2) wave loads; 3) current loads; 4) hydrostatic pressure loads; 5) inertia loads; 6) sea ice loads; 7) loads due to marine growth; 8) loads due to exceptional events (e.g. earthquake, ship impact etc.). The wind, waves, current, hydrostatic pressure and inertia loads are considered in this study. Other loads associated with sea ice, marine growth and exceptional events are ignored. These effects may play a significant role for more detailed investigation or certain offshore locations; however, for the purpose of this generic study they are deemed negligible. In this study, both ultimate and fatigue load cases are considered. For the ultimate load case, the extreme sea condition (i.e. 50-year extreme wind condition combined with extreme significant wave height and extreme current velocity) represents a severe load and therefore is taken as a critical ultimate load case. For the fatigue load case, both wind and wave fatigue loads for the normal operation of OWTs are considered. Table 2.3 presents both extreme and normal sea condition considered in this study. The rotor aerodynamic loads are presented in Table 2.4 and are taken from LaNier (2005) for a typical 5MW wind turbine. The wave loads on monopile submerged in water are calculated using the Morison's formula. The current loads are taken into account by adding the current velocity to the wave particle velocity in the drag term of the Morison's formula.

Table 2.3 Sea conditions

Item	Values	
	Extreme sea condition	Normal sea condition
Wind speed [m/s]	59.5	10
Significant wave height [m]	8.40	1.00
Wave period [s]	10.50	5.55
Current speed [m/s]	1.42	-

Table 2.4 Rotor aerodynamic loads

Load case	Thrust [kN]	Bending moment [kN-m]	Torsion [kN-m]
Ultimate	781	38.567	7,876
Fatigue	197	3,687	3,483

The optimisation algorithm that has been selected is based on Genetic Algorithms, which is a search procedure based on genetics and natural selection mechanisms, in order to search for optimum solutions, as shown in Figure 2.19. In the GA, a population of candidate solutions (also called individuals) to an optimisation problem is evolved toward better solutions. The evolution generally begins with a population of randomly generated individuals. It is an iterative process, and the population in each iteration is called a generation. In each generation, the fitness of each individual in the population is assessed, and the fitness is generally the value of the objective function in the optimisation problem. The individuals having good fitness are stochastically selected from the population, and the genome of each individual is modified through mutation and crossover operators to form a new generation. The new generation of

individuals is then used in the next iteration of the algorithm. Generally, the algorithm terminates when either a satisfactory fitness level has been reached for the population, or a maximum number of generation has been produced. The objective function to be minimised for this problem is that of the total mass subject to a series of the criteria which include (i) a deflection constraint, (ii) a stress constraint for ultimate strength, (iii) fatigue constraint based on the SN curve approach, and (iv) buckling constraint and (v) frequency constraint.

The structural optimization model of OWT monopiles is applied to NREL 5MW OWT (Jonkman et al., 2009) on monopile support structures in seven water depths, ranging from 20m to 50m. The diameter of the monopile is assumed to be increased from 5.5m to 8.5m as water depth increase from 20m to 50m. The length of the monopile substructure is assumed identical to the length of the monopile foundation. The monopile foundation is designed with a uniform thickness to facilitate its installation. The monopile substructure consists of several five-meter-length segments, and the number of segments depends on the water depth. The thickness of the monopile foundation and the thickness of each segment of the monopile substructure are taken as design variables, of which optimum values are determined using the design optimization model, which has been developed by combining the parametric FEA model and GA (genetic algorithm). The results from the optimization algorithm for the seven water depths for the monopile structure are depicted in Figure 2.20 (left plot).

The structural optimization model of OWT jacket support structure is applied to NREL 5MW OWT on jacket support structures in three water depths, i.e. 40m, 55m and 75m. For all cases, the angle between the two adjacent braces of X-braces is 110 deg, and the angle between the legs and X-braces is 37 deg. The legs are oriented with an angle of 2 deg with respect to the vertical axis. The diameter of legs is assumed to be 1.2m, and the diameter of both X-braces and mud-braces is assumed to be 0.8m. In this study, the thickness of X-braces and the thicknesses of legs at each level are taken as design variables, of which values are determined using the design optimization model. The thickness of mud-braces is assumed to be identical to that of X-braces. The results from the optimization algorithm for the three water depths for the jacket structure are depicted in Figure 2.20 (right plot).

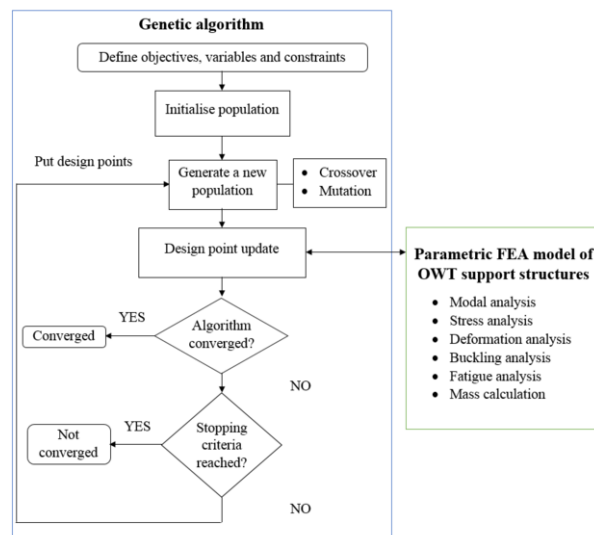


Figure 2.19: Genetic Algorithm for optimization of offshore wind turbine support structures

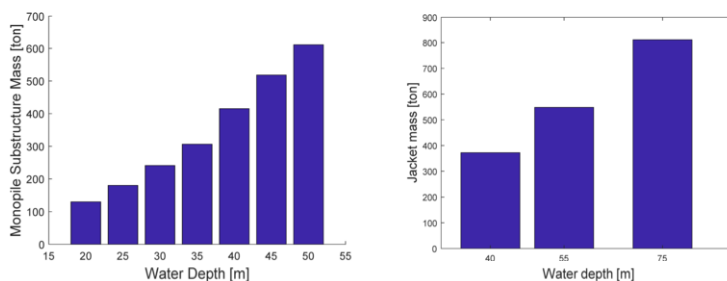


Figure 2.20: Mass of the support structures as function of water depth obtained from the optimization analysis (left: monopile; right: jacket)

### 3. WAVE ENERGY CONVERTERS

As compared to the offshore wind industry, there are no commercial wave energy converters yet. Extensive research has been carried out and led to the development of many WEC prototypes that were tested at sea. Most of these prototypes have a relatively small rated power (typically less than 300kW-500kW for a single device at small-scale, not full-scale) and have not been tested for long times (Astariz & Iglesias, 2015). However, we expect to see more WEC prototypes with increasing sizes, which may lead to a total installed capacity of as much as 26MW in Europe by 2018 (Magagna & Uihlein, 2015). We will mainly review the recent work on wave energy devices regarding numerical modelling and analysis with focus on non-linear hydrodynamic effects, CFD analysis, PTO and mooring systems, as well as model testing of single WEC devices or arrays. The initial results from the IEA OES benchmark study are summarized at the end of this section. The main categories of wave energy conversion technologies considered here are: point absorbers, Oscillating Water Column (OWC) and overtopping devices.

#### 3.1 Numerical modelling and analysis

Numerical modelling and analysis are vital for WEC design, validation and optimization. Mathematical models are essential for assessing power production, device motions, model-based control strategies and survivability. As for other offshore structures, two main modes of operation are commonly assessed: power production mode and survival mode. However, in contrast to traditional offshore engineering applications, WECs are designed to maximise power absorption with large motions, which are, therefore, intrinsic to most normal operations. Thus, nonlinear dynamics may appear, not only in survival mode, but also during power production mode. Accordingly, linear approaches originally created for traditional offshore engineering applications, may not be accurate to reproduce the behaviour of WECs (Penalba et al., 2017).

In a recent review of nonlinear numerical approaches applied to WEC behavior modelling, Penalba et al. (2017) suggest a modelling validity discretization in terms of three regions with increasing velocities, motion amplitudes and forces: 1) Linear region; 2) Nonlinear region; 3) Highly nonlinear region. 1) and 2) refer to power production mode, whereas 3) is valid for the survival mode.

Nonlinearities arise already in the wave modelling, particularly when assessing WECs in survival mode. However, Ransley et al. (2017b) reminds us that a fully nonlinear theoretical model of extreme waves does not yet exist and therefore use in their work a ‘NewWave’ linear formulation for simulating focused waves impacts on generic WEC hull forms, resorting to a fully nonlinear CFD tool.

Nonlinearities also arise in the PTO (Section 3.1.2), moorings (Section 3.1.3), and in the hydrodynamics of the fluid interaction with the WEC devices themselves. WEC control model-

ling is often coupled with the PTO system and is therefore not subject to extensive review in this section. However, recently published predictive control techniques which have an intrinsic hydrodynamic numerical model are worth mentioning. Such is the case of the study on the near-optimal control of a WEC with a deterministic-model driven incident wave prediction technique by Korde (2015). Another example is the straightforward process of assessing the impact of latching control technologies on the performance of a WEC presented by Sheng et al. (2015b). In their approach, a ‘time-out’ method is applied, where the time at which the system is latched is removed and then an ‘equivalent’ motion of the device is transformed to an approximately linear solution.

In this section, the numerical modelling and analysis of the WEC hydrodynamic loads and induced motion, PTO and mooring responses will be discussed with focus on nonlinear analysis methods.

### *3.1.1 Load and motion response analysis*

#### ***Nonlinear hydrodynamic analysis of WECs***

Approaches to solve the nonlinear hydrodynamics of the fluid interaction with the WEC bodies are addressed in what follows.

Froude-Krylov forces become nonlinear as the relative motion of the devices increases. Occurrence of parametrically excited motions can then arise, which may have drastic effects if damping is not sufficient. Furthermore, when amplitudes increase, so will the nonlinear nature of the drag forces. In this respect, Tarrant and Meskell (2016) presented an investigation on parametrically excited motions of point absorbers in regular waves, where a weakly nonlinear method was used to assess the instability regions in the roll and pitch modes of a ‘WaveBob’ model. Nonlinear drag was accounted for by a quadratic (in velocity) relationship, similar to the Morison’s formula.

Sloshing is also an important source of nonlinearities. These, however, are limited to OWC devices or other WECs which include internal fluid motion. Elhanafi (2016) studied the wave loads on a fixed offshore OWC using 2D and 3D CFD models based on RANS-VOF. Results showed that under high frequency waves, the chamber’s free surface motion is no longer flat and nonlinear effects as well as water sloshing increase, influencing the resultant forces. Furthermore, from 108 test cases in total, it was concluded that there are non-negligible differences between 2-D and 3-D computations, and between different models of the action of the PTO in an OWC.

Device slamming on the free surface, as well as wave slamming is a highly nonlinear phenomenon, very common in WECs. Of particular interest is the review on the phenomenon by Saincher and Banerjee (2016), who, among several other important conclusions, conclude that viscous effects arising from breaking-induced turbulence would increase the coefficient of radiation damping on the WEC motion equations, and thus lead to damped oscillations of the WEC. This would induce nonlinearity in the system response even in a regular wave field. Paradoxically, this additional damping could actually be beneficial if the turbulence generation is consistent and occurs for a sufficiently long duration, as an over-damped (point absorber) WEC would respond to a wider range of frequencies compared to an optimally damped WEC.

Approaches to include nonlinearities in the models can be more or less sophisticated, where increased complexity and accuracy always comes with increasing computational demand. In general, the level classification by Hirdaris et al. (2014) for more general floaters regarding numerical methods is valid also for WECs: 1) Linear; 2) Froude-Krylov nonlinear; 3) Body nonlinear; 4) Body exact - weak scatter; 5) Fully nonlinear - smooth waves; 6) Fully nonlinear.

Yet another way to include nonlinearities is through system identification models or related procedures. Ringwood et al. (2015) examined the range of tests available in a numerical wave tank from which linear and nonlinear dynamic models can be derived, from a system identification perspective. Davidson et al. (2016) proposed the use of discrete-time nonlinear autoregressive with exogenous input (NARX) models, as an alternative to continuous-time models of WEC behavior, with techniques of model identification being also presented and applied to a case study. Also related is the work by Spanos et al. (2016) who proposed a statistical linearization technique for conducting expeditiously random vibration analyses of single-point harvesters. The technique is developed by relying on the determination of a surrogate linear system identified by minimizing the mean square error between the linear system and the nonlinear one.

Unfortunately, at this point only a few WECs have been deployed at full scale and no, or very limited, data is publically available from these deployments that could be used to provide validation of a numerical model from system identification (Folley, 2016).

On the other hand, potential flow based linear methods are still commonly used as a standard tool - Folley (2016) estimates that these comprise approx. 90% of WEC hydrodynamic modelling. In addition, analytical methods are also used in initial estimates of WEC performance, particularly in assessing their main design characteristics, resorting to more or less sophisticated optimization algorithms.

Analytical or theoretical formulations are device specific. Some are formulated from first principles, whose derivation easily allows adaption to other designs at some point. Such is the exposition made by Stansby et al. (2015a), who studied a three-float broad-band resonant line absorber with surge for wave energy conversion. Other formulations address not so common WEC types with the originality or complexity of their derivation being, therefore, intrinsic. Examples of these are the study on the performance of a rigid open-ended pipe serving as an artificial upwelling pump, by Fan et al. (2016), and the prediction of ocean wave harvesting, with a piezoelectric coupled buoy structure by Wu et al. (2015). Also worth mentioning is the analysis of a cycloidal WEC performance from its radiated waves using a very simplified, yet experimentally validated, analytic formulation, by Siegel (2015), and Noad & Porter (2017), who aim at providing a more general analytic formulation to assess the performance of articulated raft WECs, avoiding its validity to very specific existing designs of this type.

The control strategy is becoming one of the key research topics for wave energy. In fact, a good control can improve the device efficiency, possibly more than doubling the average annual harvested power. For this reason, new control strategies are continuously introduced (Wilson et al., 2016).

However, control strategies rely on a model of the WEC behavior, and almost all of them are based on linear approximation of the motions. As described in Giorgi & Ringwood (2016), this may lead far from the optimum solution and in fact, nonlinearities are amplified by the control, with increased amplitude of motion of the WEC or with abrupt forces applied to it.

### ***CFD analysis and validation***

In Giorgi & Ringwood (2016), a 2D simulation of a cylindrical device in waves was run with OpenFoam (Weller et al., 1998) to optimize the control strategy. The authors found that the actual optimum is obtained with a smaller latching period than that for the linear simulation.

However, running 3D simulations of wave energy devices can be very time consuming. Bhinder et al. (2015) shows the differences in the results and computational time for a CFD calculation (with FLOW-3D) and a linear BEM solution with ANSYS AQWA of a pitching wave energy converter, as compared to the experimental data. Both solutions predict well the body motion, even though the CFD solution could take up to 3 days to run, while the linear one

takes only 8 minutes. The main difference in the solution is the higher amplitude of oscillation of the BEM that could be avoided by including a model of viscous effects, for example obtaining a damping coefficient from a free decay analysis.

In a thorough review of the computational methods by Penalba et al. (2017), they recognize that CFD calculations are necessary in some cases, for example the analysis of survival mode situations. In other cases, where the high fidelity can be sacrificed for a fast solution, it is possible to model the nonlinear effects by conducting a series of representative tests, selecting the representative data of the ‘system’, defining the fitting criteria, and identifying the system parameters.

Recent publications comparing numerical and experimental results include Penalba et al. (2017), Bhinder et al. (2017), Ransley et al. (2017a) and Ransley et al. (2017b). The CFD calculations here have been done using several solvers, namely: FLOW-3D, OpenFoam, STAR-CCM+. Most of these solvers have already been validated for a wide range of fluid flows, so, as long as an adequate mesh is used, their solutions tend to compare well with experimental data. Using CFD simulations for operational conditions can introduce significant numerical viscosity (see Penalba et al., 2017) and a poor approximation of the free surface (see Bhinder et al., 2017) or of the vorticity region (see Ransley et al., 2017b), if the mesh is too coarse. This makes the CFD calculation less appealing than linear or weakly nonlinear potential flow solutions, which are much less computationally demanding. CFD simulations are, however, critical to the study of survivability conditions (for example see Ransley et al., 2017b). In that case, small discrepancies with experimental data do not jeopardize the reliability of the fully nonlinear fluid dynamics solver in terms of free-surface behavior around structures, pressure on the device, motion of floating WEC and the loading in mooring lines.

### 3.1.2 Power take-off analysis

#### **Numerical models**

Xu et al. (2016) studied experimentally and theoretically the wave power extraction of a cylindrical oscillating water column (OWC) device with a quadratic power take-off (PTO). In numerical simulations, the quadratic PTO model was linearized based on the Lorenz’s principle of equivalent work. The developed model adequately predicted the effects of wave length and wave height on capture width ratio. Additionally, a semi-analytical model based on the work done by the drag force is able to reasonably predict the variation of the viscous loss with wave period.

Weia et al. (2017) developed a numerical model in order to investigate the adaptability of the multi-pump multi-piston power take-off system of a novel WEC. The proposed model takes into account the diffraction and radiation effects as well as the inclusion of multiple degrees of freedom for the floater elements. The model was validated by comparing the dynamics of the floater and pistons with experimental results.

Kamath et al. (2015) used CFD to simulate an OWC in a 2D numerical wave tank. Darcy’s law for flow through porous media was used to model the PTO damping on the device chamber. The model was validated by comparing the chamber pressure, variation of the free surface inside the chamber and the vertical velocity of the free surface with the experimental data. The PTO damping has a large influence on the hydrodynamics of the OWC, so the PTO damping can be used to attain the maximum possible hydrodynamic efficiency (for a given wavelength of the incident waves).

Liu et al. (2017) proposed a combined hydrodynamic and hydraulic PTO unit model in order to investigate the performance of the two-raft-type WEC. It was found that the time histories of the hydraulic PTO force resembled square waves. Thus, in regular waves, the hydraulic

PTO generally has a higher peak power capture width ratio than that obtained by using a linear PTO unit. However, this advantage was not found for irregular waves.

Nielsen et al. (2015) considered a gyroscopic PTO within a point absorber which consists of a float rigidly connected to a lever (where the other end of the lever is supported by a hinge). This type of WEC may have subharmonic or even chaotic response under harmonic wave excitation. However, when synchronization of the angular frequency of the ring to the angular frequency of the wave loading takes place, the response of the float becomes almost harmonic. This means that the generated electric power becomes almost constant in time so additional power electronics is unnecessary. The study also provides the stability conditions for the synchronized motion.

Shi et al. (2016) presented a theoretical analysis on the power take-off of a heaving buoy WEC. The governing equations were developed considering hydraulic damping of the PTO as well as the analytic solutions to describe the motion and maximum power output. Displacements and average output power of the buoy with different values of damping and inertia coefficients are presented.

### ***Energy efficiency***

Lopez et al. (2017) investigated the performance of the CECO wave energy converter including its wave energy conversion stages and the influence of the PTO system. The performance of CECO was simulated in the time domain with a BEM code. The numerical model was calibrated with the results obtained in the previous wave basin experiments. For irregular wave conditions, CECO can absorb more than 30% of the incident wave power and transmit to the electric generator up to 18% of the incident wave power.

Liermann et al. (2016) investigated the energy efficiency of a pneumatic PTO for small-scale, low cost, portable wave energy converter. Energy losses were found from: the pneumatic motor, the generator, the air preparation unit, the pumping cylinder and the accumulator.

Hansen and Pedersen (2016) presented a method for determining the optimal configuration of a discrete fluid power force system for the PTO system. The number of discrete forces and the level of these are varied within the observed configuration. The multi-chamber cylinder, the number of pressure lines and the value of the pressure in the common pressure lines were determined based on time series simulation.

Schmitt et al. (2016) presented an optimization of the PTO for an oscillating wave surge converter (OWSC). A novel method to determine the instantaneous wave excitation of an OWSC was developed based on RANS CFD simulations. Results for two regular waves were presented. Additionally, the method was used to find the optimum damping settings for an OWSC.

Negative springs is a hot topic for wave energy conversion. The reason for this is that most practical wave energy converters have relatively large restoring coefficients, which lead to large resonance frequencies and a mismatch with the wave conditions at the deployment site. Application of a negative spring could reduce the device restoring coefficient so to reduce its resonance frequency to better match the wave conditions and increase the wave energy production. The physical implementation of a negative spring in a wave energy converter may use hydraulic actuators. Todalshaug et al. (2016) have shown that it is possible to implement a system such that a negative spring could automatically be implemented, and the experimental results show an increase of more than 300% in the extracted wave energy compared to a conventional wave energy converter.

Another example of applying a negative spring in a wave energy converter has been implemented in an oscillating water column (OWC) using so called Hydrodynamic Negative Spring (HNS) (Gradowski et al., 2017). Accordingly, when the device moves downward, due to the



expanded air chamber (see Figure 3.1, left), less seawater is displaced by the floater. This reduces the buoyancy force pushing it back up, increasing its time spent below the mean water level. When the floater moves upward, the stored seawater in the expanded air chamber is returned to the sea, displacing an increased volume of seawater (see the right plot in Figure 3.1). This special design of an expanded air chamber in the spar OWC could increase the buoyancy force pushing up on the floater, and prolong its upward oscillation, that is, the resonance period of the device can be increased for a better match to the target waves.

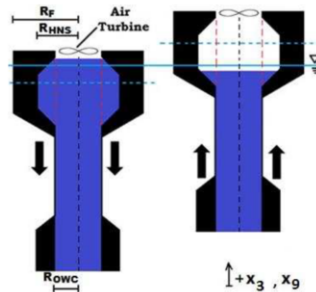


Figure 3.1: Negative spring implementation in a spar OWC (Gradowski et al., 2017)

### 3.1.3 Mooring analysis

#### *Effects of mooring systems on WEC operability and survivability*

Accurate assessment of the mooring lines is fundamental both in survivability conditions and in normal operating conditions, especially when the mooring is part of the energy harvesting process. The importance of the interconnection between the device motion and the mooring line was shown in Hann et al. (2015). There, the response to extreme waves of a single taut moored floating point absorber was measured when mooring lines purposely designed to generate a snatch load where in place. The extreme waves were generated by focused wave groups. It was found that for a dynamically responding floating body, the mooring loads are dependent on the displacement history, thus a single focused wave alone cannot be used to obtain an accurate assessment of extreme mooring loads.

Another example of the of strong interconnection among the different parts of a WEC device can be found in Fonseca et al. (2016), where an oscillating water column spar-buoy WEC was experimentally investigated. It was noticed that the closure of a stop valve (in order to protect the WEC turbine) may reduce the turbine-induced damping effect and cause amplification of the WEC movements. Consequently, in the more energetic sea states this might aggravate the loads on the mooring system and ultimately compromise the survival of the WEC system.

More general work by Paredes et al. (2016) shows how a better choice of mooring system can affect power production, displacements and extreme tensions.

A detailed validation of the numerical model of a wave energy mooring system against the tank test results was described by Harnois et al. (2015). A compliant three leg catenary mooring system using nylon ropes was investigated. Static, quasi-static, decay, regular and irregular wave tests were conducted. After the calibration of several hydrodynamic parameters, the numerical model demonstrated good agreement with the experiment. In addition, comparisons with the field test were conducted and large differences with numerical results were found, mainly because of uncertainties in the anchor position.

Yang et al. (2016b) investigated the effect of the superimposed wave-frequency random motion on the low-frequency mooring line damping through time domain simulations. Moreover, the random motions of the vessel were represented by an equivalent sinusoidal motion in or-

der to compare the effect of the superimposed sinusoidal motion and random motion. It was found that the response amplitude operator plays a dominant role in determining the amplification factor of the mooring line damping. The results also indicated that the effect of superimposed random motion is small as compared with the superimposed equivalent sinusoidal motion.

Palm et al. (2016) presented a fully coupled CFD mooring analysis of moored floating objects. A two-phase Navier-Stokes (VOF-RANS) model was coupled with a high-order finite element model of mooring cables. This study was made without the presence of a PTO system. An excellent match between the experimental and the numerical results for the surge decay test was found. Moreover, the model is able to capture the non-linear wave height dependence of the response amplitude operators seen in the experiments.

#### ***Fatigue assessment***

A comparison of the simulation procedures for the fatigue analysis of WEC moorings was conducted by Yang et al. (2016a). A floating cylindrical WEC with four spread mooring lines was chosen for the case studies. The dynamics of the WECs were simulated using both coupled and de-coupled models in the time-domain. The fatigue damage was calculated using the stress-based approach and the rain-flow counting method. It was established that the coupled and de-coupled simulation procedures generate different fatigue results for the studied cases under moderate wave conditions. Since the CPU times are about the same for the two simulation procedures, the coupled simulation procedure is considered as the better option for initial fatigue design assessment. Two different numerical implementations of the cable dynamics were considered and it was found that they have significant impact on final fatigue results.

The impact of biofouling on WEC systems with respect to energy absorption and fatigue lives of the cables and moorings was investigated by Yang et al. (2017). Coupled response analyses were conducted including hydrodynamic and structural response. The biofouling was modelled as an increase in the submerged weight and drag coefficients of the moorings and cables. The results showed that the biofouling can reduce the total power absorption by up to 10% for a WEC system which has been deployed for 25 years. Additionally, the fatigue life of the mooring lines decreased by approximately 20%.

#### ***Parametric studies and optimization***

Optimization of a three-tether submerged point absorber wave energy converter was conducted by Sergiienko et al. (2016). The mooring configuration allows for the extraction of power from surge, heave and pitch motions where the relative contribution from each motion is different and depends on the inclination angle of the mooring lines. Two generic buoy shapes were considered, a sphere and a vertical cylinder. Optimization of the inclination angle was conducted through a frequency domain analysis. For the sphere, the optimal configuration was one where the tethers are orthogonal to each other. For the cylinder, an optimal angle between the tethers depends on the ratio between the cylinder height and diameter.

Wang et al. (2016b) studied a coaxial-cylinder WEC system consisting of a floating vertical inner cylinder and an annular outer cylinder. The study investigated the influence of the mooring line stiffness on the performance of the WEC system. The limiting cases of zero and infinite mooring line stiffness were also examined. It was concluded that the limiting cases can be viable, depending on the installation site depth, and that a poor choice of stiffness can eliminate the relative heave motion between the inner and the outer cylinders and lead to very low power extraction.

#### ***Novel concepts***

A novel mooring tether was developed by Thies et al. (2014). The mooring tether combines soft elastomeric and stiff thermoplastic material components within a single assembly. Elastic

response through the elastomeric component is intended for operational conditions. Stiff, non-linear response, is achieved by the thermoplastic component to withstand higher loads during storm conditions. The point of transition from the elastic to the compressive element can be designed for a particular application. Fatigue and creep analysis showed that a lifetime of 5 to 10 years is feasible.

Luxmoore et al. (2016) presented the Intelligent Active Mooring System (IAMS). The main intention was to minimize extreme and fatigue loading in mooring lines through a load–extension curve that is variable during operation and can be adjusted to the prevailing environmental conditions. The IAMS design is based on a hollow braided wire rope. A flexible water filled bladder is set inside the hollow braid to resist reductions in the braid diameter, during rope extension, through controlled hydraulic pressure. An analytical model of IAMS was developed and validated against physical semi-static tests. Next, numerical validations were performed where a conventional mooring line is replaced by an IAMS. Fully dynamic simulations with real environmental data showed that the IAMS device can provide a significant reduction in the line tensions. Moreover, active control of IAMS can be used for tuning the mooring system to enhance the motions of a typical small WEC.

### 3.2 *Physical testing*

Physical testing is very important for verifying new concepts, validating numerical tools, and identifying technical problems and phenomena that were not fully understood or not revealed by analytical or numerical assessment. In this section, we will review some recent work on model testing and field testing of wave energy converters.

#### 3.2.1 *Laboratory testing and validation of numerical tools*

Model testing of wave energy converters in hydrodynamic labs is performed mainly to verify new concepts in the early development stage with respect to the power absorption performance, and to validate numerical models for both operational and survival conditions. In 2014, the International Towing Tank Conference (ITTC) issued guidelines for wave energy device experiments (ITTC, 2014). It advises to use test facilities for devices with Technology Readiness Level (TRL) from 1 to 6, that is from the validation of concept to the sub-system and system validation in laboratories and/or simulated operational environments. According to the ITTC, for a higher TRL, tests should be carried out at large or full-scale.

The ITTC guidelines also highlight that even though towing tanks (suitable for long-crested waves), ocean basins (for both long- and short-crested waves) and ocean basins with wave and current facilities present a well controlled environment, a severe limit to their use is due to both wave heights and run durations for the large scale models required by WEC testing. In fact, it recommends that the corresponding duration of runs in full scale should be of 30 minutes in irregular waves for statistical validation and of 3 hours for the survivability tests. Both the physical limit of the maximum wave height generated by the wave makers and the need to minimize the build-up of reflected waves and to preserve the quality of the wave field, can severely limit the scale factor that is chosen for the model. In the end, however, it is necessary to compromise with the limits of the laboratories and the need for certain scale factors by taking into account the contamination from facility induced uncertainties. For example, in O’Boyle et al. (2017), where it was not possible to fully remove all tank contamination, the effect of WEC arrays on the wave field was studied by mapping the baseline variations in wave climate in the basin without any models installed. This has allowed the identification of the wave disturbance pattern and of its dependence on the array layout, on the wavelength to device spacing ratio, and on the applied PTO damping. In Costello et al. (2014), the uncertainty in the wave generated by the wave maker has been taken into account in the evaluation of the performance of a Model Predictive Control (MPC) strategy. The new strategy was applied to the study of a 1:20 scale model for the WaveStar machine in irregular sea, with wave

spectra representative of real-life conditions. The results sought to demonstrate that the estimated wave forces and the measured ones were close, and that this has allowed the maximization of the extracted power, disregarding the effects of the possible errors in the wave generation.

More importantly, the ITTC guidelines stressed that, whatever PTO model is used, a suitable characterization of the damping system should be carried out before the installation in the model. This should be done together with identifying the ‘uncertainties associated with the reciprocating nature of many wave energy devices/PTOs’, because the overall behavior may not be directly comparable with the individual behavior of single components under steady-state conditions.

### ***Testing of power take-off (PTO) components***

In a small-scale model test, it is important but difficult to design a representative power take-off (PTO) system corresponding to the full-scale concept. A PTO system is often simplified as a Coulomb or linear damper, an orifice load and sometimes an active control system in the lab tests. More details can be found in the ‘Handbook of Ocean Wave Energy’, edited by Pecher & Kofod (2017).

An orifice plate is often used in the model test to represent the PTO (air turbines) for OWC devices. Fleming & Macfarlane (2017a) suggested to use separate flow coefficients for air inflow and outflow of an orifice to better estimate the air volume flux and therefore the power absorption. It also outlined a method to use the pressure measurements rather than the wave elevation data to estimate the air volume flux. In their second paper (Fleming & Macfarlane, 2017b), the detailed flow field around a 1:40 OWC model was revealed and assessed based on 2D PIV measurements.

Experimental and numerical studies (Colicchio et al., 2017) were carried out for a bottom-fixed OWC concept WaveSax at CNR-INSEAN, Italy. A 1:5 scale model equipped with an immersed Wells turbine was tested. In particular, the power performance of the three-blade, four-blade and five-blade turbines with angular speed control was studied in detail. The comparison between the numerical and experimental results indicates that the simplified porous disk is sufficiently accurate to model the Wells turbine.

Up to now, real-time hybrid testing techniques have not been used for testing WECs. In a hybrid test, parts of the system and the related dynamics are physically scaled and modelled in the lab, while the remaining parts and the related physics are numerically simulated and applied via actuators. In the chapter on offshore wind turbines, this technique has been discussed for testing of floating wind turbines (Chabaud, 2016). A similar technique might be applicable to represent PTO systems and loads in a model test for WECs. In an opposite way, when testing the PTO performance, the PTO loads might be obtained from a numerical WEC model and applied in the actual test. This was done by Li et al. (2017) for a PTO system of a point absorber with an electromagnetic generator and a mechanical motion rectifier (MMR) in a dry test. The MMR was used to convert bi-directional rotation into unidirectional rotation to improve the efficiency.

Unfortunately some errors in the PTO characterization and scaling have been noted in several cases, as highlighted in Falcao & Henriques (2014) for the correct scaling of the immersed part and the air chamber of OWCs. In particular, if Froude scaling applies to the immersed part, the air chamber either has the same scale factor, but the air inside it (and around it) has a reduced atmospheric pressure or the atmospheric pressure is kept unaltered and the size of the air chamber is scaled with a ratio that depends on the polytropic behavior of the air. It is also noted that ‘in many published papers reporting OWC model testing these similarity rules were simply ignored’ with substantial errors in the prediction of the extracted power in full scale.

### *Testing of a single device*

#### • *Power performance tests*

When developing new WEC concepts, lab tests, in addition to numerical studies, are normally performed to verify the concepts with focus on power performance characterization.

At the University of Manchester, a three-body WEC (called M4) was developed and tested in their wave tank. The concept consists of a small bow float, a medium mid float and a large stern float in the direction of wave propagation. The bow and mid floats are rigidly connected, while the stern float is connected to the hinge point above the mid float, where a hydraulic PTO system is placed. This concept is shown by an experimental study at a scale ratio of 1:40 to have a high energy capture width ratio (Stansby et al., 2015b). A time-domain model based on the linear diffraction theory has been developed (Sun et al., 2017) and the comparison against the experimental results indicates an excellent prediction of relative rotation of the floats and beam bending moment and a slight over-prediction of power capture in unidirectional waves. In another study (Stansby et al., 2017), the power performance of multi-body configurations (from 1-1-1, 1-2-1, to 1-3-3, 1-3-4) are numerically studied and compared for four different offshore sites. Here, the number of buoys in the first, second and third rows of the system along the wave propagation direction was indicated, respectively. For example, the configuration 1-1-1 is shown in Figure 3.2. The capture width ratio increases significantly from the three-body system to the eight-body system.

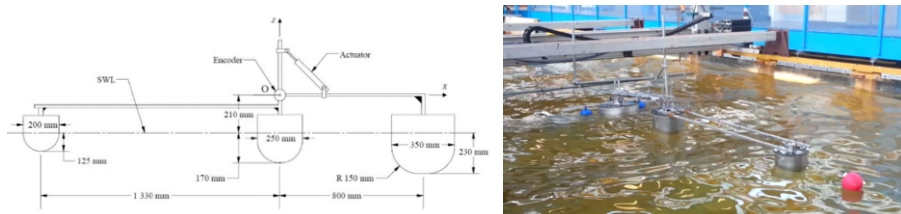


Figure 3.2: The three-body WEC concept M4 (Stansby et al., 2017)

A heaving-buoy concept (as shown in Figure 3.3) was developed by CorPower Ocean (Todalshaug et al., 2016) and tested at ECN in France, at a scale ratio of 1:16. A novel pneumatic solution (WaveSpring) for inherent phase control (that can provide a negative spring effect on heave motions), was developed and shown in the test to increase the absorbed energy by a factor of three as compared to a pure linear damper. On the other hand, the dynamic forces in the conversion machinery have the same magnitude as the operations without the negative spring module, as shown in Figure 3.3. Moreover, the WaveSpring unit can be tuned to give both resonant and broad-banded responses for operational conditions, while it can be detuned to reduce the responses in high-energy sea states.

Regarding OWCs, an experimental study (Vyzikas et al., 2017) on four bottom-fixed OWCs was performed with a scale ratio of 1:13, mainly to study the geometric effect on the power efficiency. They include a conventional OWC in a vertical seawall with a horizontal slit opening at the bottom, a conventional OWC combined with a submerged slope in the front representing part of a real breakwater, an improved design of the U-shape by Boccotti (2007a, 2007b), and the improved U-shape OWC combined with a submerged slope. Tests in regular and irregular waves from this study further confirmed the better power performance of the U-shape design as compared to the conventional one. Adding a submerged slope will also increase the power capture of the OWC.

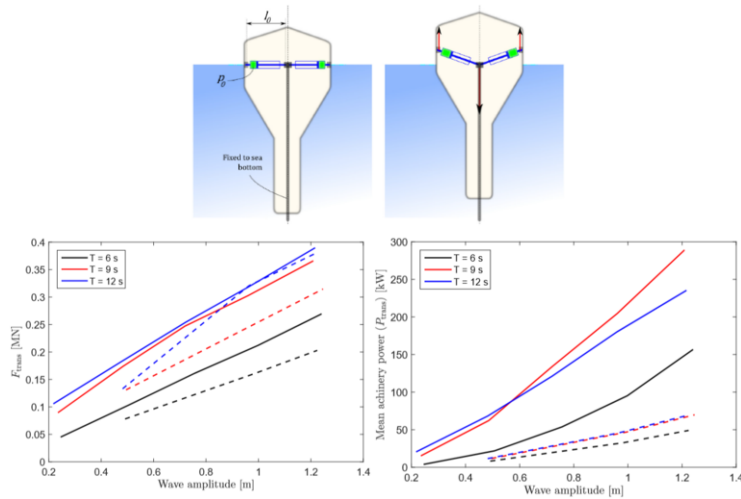


Figure 3.3: The heaving-buoy WEC concept (top) developed by CorPower Ocean and the dynamic force amplitude in the conversion machinery and the average absorbed power for regular wave conditions (Solid line: results with WaveSpring; dash lines: results without WaveSpring.) (Todalshaug et al., 2016)

- **Numerical model validation tests**

Traditionally, numerical methods based on linear potential theory are the main tools to study the dynamic behaviour of WECs in operational and survival conditions. In recent years, CFD analyses have been more often applied and experimental results are used to validate CFD calculations. CFD analysis is more useful when nonlinear wave loads and responses become important.

A wave tank testing for the 1:33 scale model of a flap-type Floating Oscillating Surge Wave Energy Converter (FOSWEC) was performed at the Oregon State University's Directional Wave Basin (Bosma et al., 2016; Ruehl et al., 2016), as shown in Figure 3.4. The test was mainly to generate a large database for validation of the numerical tool WEC-Sim, developed by Sandia National Laboratories and the National Renewable Energy Laboratory (NREL). Up to now, a preliminary validation study was performed on motion decay results. A numerical model taking into account the nonlinear hydrostatic and hydrodynamic loads seems to agree much better with the experimental results as compared to the linear model.

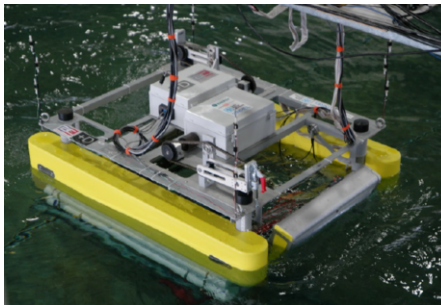


Figure 3.4: The 1:33 scale model of the FOSWEC concept (Ruehl et al., 2016)

In the study by Rafiee & Fievez (2015) on their point absorber CETO, numerical predictions of the motions and the PTO loads using linear time-domain analyses and nonlinear OpenFOAM simulations were compared to the experimental data for operational wave conditions. The model test at 1:20 scale was performed at the FloWave tank at the University of Edinburgh, UK. The linear model is found to over-estimate the motions and the PTO loads because it does not consider the instantaneous wave elevation and position of the point absorber, while the CFD prediction agrees much better with the experimental results.

A novel overtopping WEC concept, WaveCat, was developed and tested at a scale ratio of 1:30 at the Ocean Basin of the University of Plymouth (Allen et al., 2017). It consists of two symmetrical hulls joined at the stern via a hinge (allowing the relative angle between the hulls to change depending on the sea state) and a catenary anchor leg mooring. No PTO system was modelled in the test. Unsteady RANS CFD analysis using STAR-CCM+ was performed to predict the heave and pitch motions of the device in regular waves. A good comparison with the measurements was obtained, but the accuracy of the CFD analysis was less for heave motions in large waves.

Elhanafi et al. (2017a) performed a model test of a 1:50 bottom-fixed OWC for regular wave conditions in the towing tank at the University of Tasmania, Australia. The wave elevation and the air pressure in the OWC chamber were measured and compared with the RANS CFD calculations using STAR-CCM+. A very good agreement was obtained for the 3D CFD model, while the 2D CFD model significantly over-estimates the hydrodynamic efficiency of the OWC device.

- **Survivability tests**

In the EU FP7 MARINA Platform Project, model tests of the three combined wind and wave concepts were performed, including a test at CNR-INSEAN, Italy on the Spar-Torus-Combination (STC) concept and a test at ECN, Nantes on the Semi-submersible-Flap-Combination (SFC) concept. A summary of the experimental and numerical studies of these two combined concepts can be found in Gao et al. (2016).

In addition to the functionality test of the STC concept (Wan et al., 2016a) with focus on the single torus-type WEC power performance, the tests with two survival modes of the WEC (one with the torus fixed to the spar at the mean water level and the other at a submerged position) in extreme wind and wave conditions were also performed (Wan et al., 2015; Wan et al., 2016b). Large motions and water entry/exit of the torus (which leads to slamming loads on the bottom of the torus) were observed for the survival mode when the torus is placed at the mean water level, mainly due to the heave resonance. In this case, numerical simulations based on linear potential theory fail to predict the loads between the spar and the torus (Wan et al., 2015), while the numerical model with the consideration of slamming loads gives a much better agreement with the experimental results (Wan et al. 2017). The experiment also reveals that the STC has much smaller motions in the survival mode with the torus submerged. As compared to the STC concept, the SFC concept is a semi-submersible wind turbine with three submerged flap-type WECs, and the experiments indicate small motion responses in both operational and survival conditions (Michailides et al., 2016a and 2016b).

A survivability model test of a floating OWC concept with intact and damaged mooring lines was performed in the towing tank at the University of Tasmania (Elhanafi et al., 2017b). The mooring system used was a taut-line system with four vertical lines and the damaged condition had one broken line. A CFD analysis for both intact and damaged mooring conditions was performed and compared well to the experimental results of the regular wave cases. The experiment also revealed that the largest mooring line tension in either intact or damaged condition is not necessarily correlated to the largest waves in an irregular wave train. This is mainly due to the dynamic characteristics of the system.



### *Testing of an array*

There is an increasing interest in studying the hydrodynamic interaction and the power performance of WEC arrays by lab testing. The WECs in an array might be mechanically connected, as in McDonald et al. (2017) or have independent motions as in Ruiz et al. (2017) and Stratigaki (2014).

In the work done by McDonald et al. (2017) and Ewart et al. (2017), model tests of the Albatern 12S WEC concept in a single-device configuration and a Hex-array configuration have been performed at 1:18 scale at the FloWave tank at the University of Edinburgh, UK, as shown in Figure 3.5. The single device is actually a floating WEC of four point absorbers connected via rigid beams and articulated joints, while the Hex array consists of nine interconnected point absorbers. The articulated joint allows for relative rotational motions of the point absorbers and an introduction of the PTO system with a linear damper. The experimental results show that the mechanical coupling as used in this study can potentially improve both the magnitude and the smoothness of the produced power per device and meanwhile reduce the mooring loads per float.

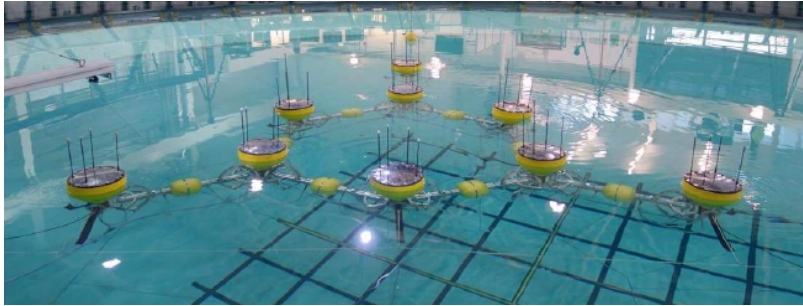


Figure 3.5: The Hex-array of the Albatern 12S WEC concept at the FloWave tank (McDonald et al., 2017)

Ruiz et al. (2017) did a model test on an array of five independent point absorbers (Wavestar WECs) under regular and irregular seas at a scale ratio of 1:20 at the deep-water wave basin at Aalborg University, see Figure 3.6 (left picture). Linear control strategies were accurately implemented in the PTO system via an electric motor. The purpose was to validate the numerical tool they developed for hydrodynamic analysis of WEC arrays. It was shown that the power prediction error from the numerical tool is typically less than 23% with a positive average error of 8%.

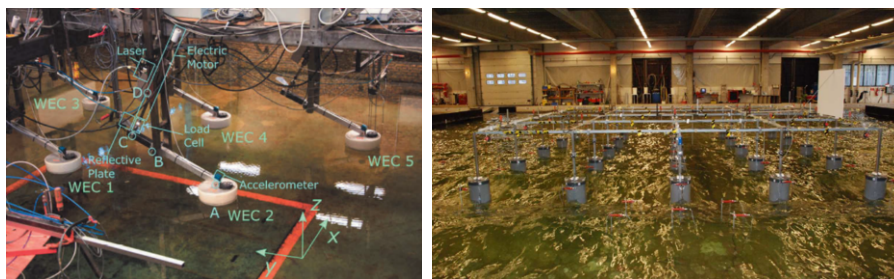


Figure 3.6: The array of five Wavestar WECs (left) in the deep-water ocean basin at Aalborg University (Ruiz et al., 2017) and the 5\*5 array of points absorbers (right) at DHI (Stratigaki, 2014)



In the PhD thesis work by Stratigaki (2014), a large-scale experimental work has been performed on an array of 5\*5 point absorbers with constrained heave motions at the DHI ocean basin, Denmark, as shown in Figure 3.6 (right picture).

The purpose was to study the intra-array interactions and the extra-array effect of the WECs in terms of wave field modifications. Therefore, the wave elevations inside the array and at the windward and leeward sides of the array were extensively measured. The motions of the WECs were also measured and used to derive the power production with an applied linear damping for each WEC. The time-averaged power output of the WECs in an array for long-crested and short-crested irregular waves are shown in Figure 3.7, as a percentage difference as compared to that of an individual WEC. The power output of the WECs in an array varies significantly. A positive effect on the power absorption was observed for almost half of the WECs for the long-crested wave conditions and the largest positive effect of about 50-55% increase was found for the WECs in the second and third rows inside the array. Only negative effect was found for all of the WECs for the short-crested wave conditions, with a largest decrease of 60%. A guideline on WEC array testing was recommended and the experimental data can be used for validation of numerical tools like WAMIT (2016) or MILDwave (Troch, 1998).

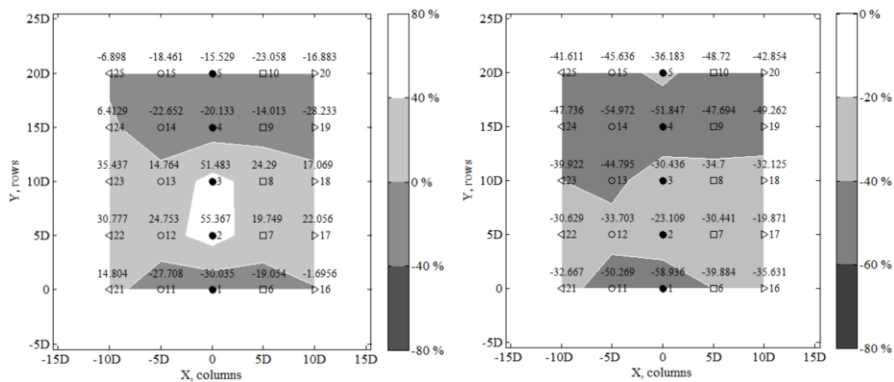


Figure 3.7: Difference percentages in non-dimensional time-averaged total power output between tests with an array and with an individual WEC for long-crested irregular waves of  $H_s=0.104m$  and  $T_p=1.26s$  at model scale (left) and for short-crested irregular waves of  $H_s=0.104m$ ,  $T_p=1.26s$  and the spreading function  $s=10$  (right) (Waves propagate from bottom to top and WECs are marked and numbered.) (Stratigaki, 2014)

### 3.2.2 Field testing

The use of real sea test sites for WECs is becoming compelling because of the limits in simultaneous scaling of mechanical, fluid-dynamic and electric components in labs. Most of the time, each part is tested separately and linearized models are used to take into account the others. The main problem comes from the non-linear nature of each of these parts or difficulties in reproducing the scaled effect (e.g. Falcao & Henriques, 2014; Falcao & Henriques, 2016). For these reasons, as soon as the WEC reaches a high TRL (technology readiness level) (Mankins, 1995), full (or almost full scale) tests are necessary to make sure that the full system is optimized and to implement the optimal control system in real sea conditions.

The availability of open-sea test sites is growing together with these needs. They are restricted regions of the sea possibly furnished with: 1) hydrographic and current surveys, 2) wave climate studies and/or historical collected wave data; 3) mooring configurations; 4) wave buoys, 5) grid connection; 6) observation towers; 7) instrumentation cables to onshore facilities, 8) data acquisition systems, 9) onshore facility; etc.

Most of these are shortlisted in the OES (Ocean Energy Systems) annual report (OES, 2016). There are eight of them in the US and eight in Europe (MARINET2, 2017), that can be used for R&D of new devices for a sufficiently long time. Among them, the BOLT Lifesaver was installed in March 2016 in the US and has been in operation for 78% of the 280 days of testing, producing a total of 17955kWh at an average power of 3.4 kW (OES, 2016).

New facilities are arising around the world, for example in Chile, where the Chilean Government's economic development organization CORFO (Corporación de Fomento de la Producción) is setting up a centre of marine energy R&D excellence in Chile, named Marine Energy Research and Innovation Centre (MERIC) (<http://www.meric.cl>).

Many other deployment sites have been chosen and equipped for the development of a specific technology. An outstanding example is the Carnegie Wave Energy Research Facility (<http://www.carnegiece.com/wave/research-facility>). It has been used for the development of the CETO technology that has been the world's first array of wave power generators to be connected to an electricity grid.

However, as shown in Cahill (2014), it is unlikely that a test site can reproduce, at reduced scale, the wave climate of the deployment site. However, a combined analysis of numerical data, wave basin and field testing can provide an accurate estimation of the expected performance, given a sufficiently long deployment time.

Once again, the CETO system is an outstanding example, it is using combined field testing, both in its own site and at the WaveHub later in 2018, and towing tank tests (at Plymouth University) to optimize some parts for its new generation technology (ASX, 2016).

In addition, in the last few years, there are many WEC devices that were deployed and tested in China (Xia et al., 2014). These field testing activities were coordinated by the Administrative Centre for Marine Renewable Energy (ACMRE) under the State Oceanic Administration (SOA) in China (Y.C. Chang et al. 2017). Some of the tested concepts are listed here, including the ones with a longer testing period at sea and the ones with a rated power larger than 100 kW, as shown in Figure 3.8.

The 10kW Jida I floating WEC of ten oscillating buoys (Wang et al., 2012) and the 10kW three-buoy WEC from Zhejiang Ocean University 15 (Xia et al., 2014) were tested for more than 150 days, both in 2015. However, the average efficiency of these two concepts was only about 15%. Similar to the Salter Duck concept, DUCK III (Yao et al., 2016), a 100kW floating WEC, was tested in 2013. The sea trial demonstrated a high energy capture efficiency, but the stability of the concept needs to be improved. As a continuation, the 100 kW prototype of Sharp Eagle Wanshan was deployed for testing offshore the Wanshan Islands in 2015. It was found in the test that at wave period between 4~6.5 seconds and at wave height between 0.6~1.8 meters, the energy conversion efficiency remains above 20% and the highest efficiency reached 37.7% (Sheng et al., 2015a).



Figure 3.8: Prototypes of the wave energy converters tested in China (from left, 10kW Jida I (Wang et al., 2012); 10kW three-buoy WEC (Xia et al., 2014); 100kW DUCK III (Yao et al., 2016); 100kW Sharp Eagle Wanshan (Sheng et al., 2015a))

### 3.3 Design rules and standards

As early as in 2005, Carbon Trust (UK) commissioned DNV to establish a standard for design and operation of wave energy converters (Carbon Trust, 2005). The standard essentially provides interpretation and guidance on the application of existing Codes and Standards (mainly from industries such as Offshore and Maritime). To streamline the development of this nascent sector, IEA-OES has organised international collaborations to implement guidelines and recommendations (reports can be downloaded at <https://www.ocean-energy-systems.org/publications/oes-reports/>), meanwhile the European project Equimar has also established similar practice and guidelines (deliverables can be downloaded at <http://www.equimar.org/equimar-project-deliverables.html>).

More recently, international efforts have been made to standardize the development of wave energy technologies and to provide a standardized assessment method, such as the rules and standards for marine renewable energy (wave and tidal energy (Cornett, 2014)). The International Electrotechnical Commission (IEC) has organized international experts from the relevant countries to work on the specific task of developing the technical specifications (which will finally be developed to be standards). The development of a technical specification must undergo the following stages: from the proposal of the task, to committee draft (CD), to draft technical specification (DTS) and technical specification (TS), and finally to standard. In the staged development, the member countries will make recommendations and comments on the documents, and the project team will make all the modifications, but the Technical Specification (TS) must be approved by the voters from the relevant countries. So far, the published TS includes:

- Marine energy- Wave, tidal and other water current converters- Part 100: Electricity producing wave energy converters- power performance assessment, published in August 2012.
- Marine energy- Wave, tidal and other water current converters- Part 10: Assessment of mooring system for marine energy converters (MECs), published in March 2015.
- Marine energy- Wave, tidal and other water current converters- Part 101: Wave energy resource assessment and characterisation, published in June 2015.
- Marine energy- Wave, tidal and other water current converters- Part 102: Wave energy converter power performance assessment at a second location using measured assessment data, published in Aug. 2016.

Some of the TS are being applied in technology development or in research work. Some other technical specifications are still under development, including the guidelines for the early stage development of wave energy converters: Best practices and recommended procedures for the testing of pre-prototype scale devices (IEC62600-103); and the electrical power quality requirements for wave, tidal and other water current energy converters (IEC62600-30).

### 3.4 *ISSC contribution to the IEA OES benchmark study*

The Ocean Energy Systems technology collaboration programme (OES) is an intergovernmental collaboration between countries, which operates under a framework established by the International Energy Association (IEA) in 2001. There are currently 20 member countries, and the goal of the alliance is to advance research, development and demonstration of conversion technologies to harness all forms of renewable energy from the ocean. In September of 2016, OES Task 10 – WEC modelling verification and validation was kicked off with a meeting of 20 participants from 10 countries. The task will run for 5 years, and the goals of the task are:

1. To assess accuracy, and establish confidence in the use of numerical models
2. To validate a range of existing computational modelling tools
3. To identify uncertainty related to simulation methodologies in order to:
  - a. Reduce risk in technology development
  - b. Improve WEC energy capture estimates (IEC TC 102)
  - c. Improve loads estimates
  - d. Reduce uncertainty in LCOE models
4. Define future research and develop methods of verifying and validating the different types of numerical models required under both operational and survival conditions.

Participants from the National Renewable Energy Laboratories (NREL) and the Sandia National Laboratories, both in the USA, took a leading role in getting the benchmark study up and running. In particular, they emphasized important lessons learned from their experience with several earlier benchmarking efforts: WEC-Sim (2017), WEC3 (Combourieu et al., 2015) and FONSWEC (2017). Experience was also brought to bear from similar efforts carried out by the IEA on Wind energy: the OC3- OC5 projects (IEA, 2017). Based on these earlier studies, the following recommendations were made:

- Start simple, e.g. single body/single DOF/simple geometry
- Minimize the number of variables
- Experiments must be performed with validation of numerical models in mind
- Uncertainty must be assessed throughout the experimental campaign. Repeated tests are a minimum here
- Frequent working meetings should be held

It was also decided that all work considered during this task should be made publicly available in order to help all developers. Participants were encouraged to seek local funding to support their participation in the Task.

A summary from Phase I of the study was presented at the EWTEC2017 conference in Cork, Ireland (Wendt et al., 2017). Phase I considered a code-to-code comparison using a floating sphere with a single degree of freedom in heave (see Figure 3.9). Calculations were made first for a decay test, then using regular waves of three different steepness values, and finally with three irregular wave conditions. For each wave condition, the sphere response (and/or forcing) was computed in the free unrestrained case, with an external (linear) optimal PTO damping, and in the fixed (no motion) condition. Participants used numerical models based on linear, weakly nonlinear and fully nonlinear potential flow, as well as CFD. Agreement among different codes was generally very good. An example is shown in Figure 3.9, which shows a very large amplitude decay test with the initial displacement equal to the sphere radius. The linear, weakly nonlinear and fully nonlinear calculations show distinct grouping in their predictions. See Wendt et al. (2017) for more details on the comparisons.

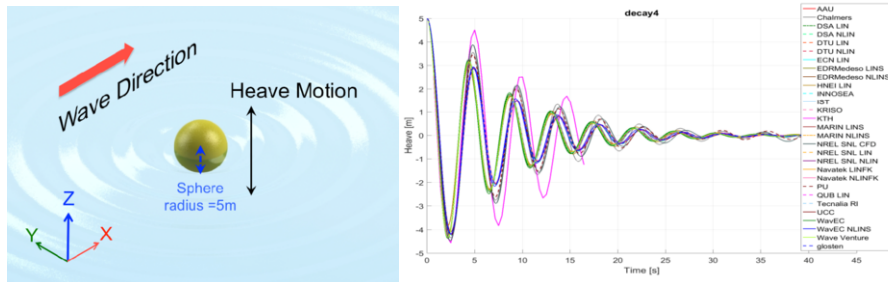


Figure 3.9: The Phase I case of a heaving sphere (left) (Courtesy of Kim Nielsen) and comparison of numerical solutions for a large-amplitude decay test (right) (Courtesy of Fabian Wendt)

Phase II of the project is currently being defined. Depending on the priorities of the participants, this could go in one of four possible directions:

- Focused wave interaction with either the floating sphere from Phase I, or a cylindrical buoy with a hemispherical bottom for which experimental measurements are available
- Comparison with experimental data for two more complicated WEC devices from the study by (Beatty et al., 2015)
- Introduction of control strategies for the case from Phase I
- Adding multiple complexities to the case from Phase I including: additional degrees of freedom, nonlinear PTO forcing (including end-stops) and a mooring system

Reporting from Phase II will appear in 2018. To participate in the study, contact Fabian Wendt (Fabian.Wendt@nrel.gov).

#### 4. TIDAL AND OCEAN CURRENT TURBINES

Tidal range and tidal current technologies are the two basic technologies that convert the tidal energy into electricity. Tidal range devices harvest the potential energy due to the difference in head between ebb tide and flood tide, while tidal current turbines convert the kinetic energy due to tidal stream into electricity. In this report, we mainly discuss tidal current turbines. In addition, ocean current can also be used to generate electricity by current turbines, but this technology is less developed and will not be discussed here.

##### 4.1 Recent development

In the last decade, there are a number of research studies on tidal current (or marine hydrokinetic) turbines worldwide and in particular in Europe. A list of the European projects under the FP7 and Horizon 2020 programmes can be found in Segura et al. (2018), including the completed projects, for example, CLEARWATER ([http://cordis.europa.eu/project/rcn/185364\\_en.html](http://cordis.europa.eu/project/rcn/185364_en.html)) coordinated by Atlantis Operations Ltd., SEAMETEC ([https://cordis.europa.eu/project/rcn/194749\\_en.html](https://cordis.europa.eu/project/rcn/194749_en.html)) by Eire Composites, and the ongoing projects, such as D2T2 ([http://cordis.europa.eu/project/rcn/207451\\_en.html](http://cordis.europa.eu/project/rcn/207451_en.html)) coordinated by Nova Innovation, FLOTEC ([https://cordis.europa.eu/project/rcn/199964\\_en.html](https://cordis.europa.eu/project/rcn/199964_en.html)) by Scotrenewables Tidal Power Limited, DEMOTIDE ([https://cordis.europa.eu/project/rcn/207512\\_en.html](https://cordis.europa.eu/project/rcn/207512_en.html)) by DEME. Many of these projects focused on the demonstration of full-scale large-size tidal turbine systems, components (such as blades, drivetrain) or condition monitoring techniques. In particular, tidal current turbines are being deployed, at full scale in the marine environment.

The decommissioning of the 1.2MW SeaGen turbine will be conducted in 2018 (Figure 4.1) after 10 years of operation in the Strangford Narrows (Northern Ireland, UK). During operation SeaGen has delivered more than 10GWh to the local electricity grid. It is important to

note that the turbine is being decommissioned and removed at the end of the consented period for the demonstration project.



Figure 4.1: Wake behind the SeaGen monopile in Strangford Narrows (Northern Ireland, UK) (left) and blades that are out of water (right)

At the same time, Atlantis Resources recently deployed the fourth megawatt scale turbine as part of the MeyGen project in the Pentland Firth (Scotland, UK) (Tidal Energy Today 2017), forming the highest capacity, grid connected, turbine array to date. Nova Innovations completed the first grid connected turbine array in Bluemull Sound (Shetland, UK) earlier the same year (Morton, 2017). Commercial turbines (as shown in Figure 4.2) are being developed by Atlantis, Voith Hydro, Alstom TGL, DCNS, Hammerfest, Schottel, Verdant and others and are being deployed in several countries including the UK, France, Canada, US and China. A full survey can be found in the annual report of the IEA Ocean Energy Systems group (OES, 2017).



Figure 4.2: Commercial turbines developed by Atlantis (top, left), Voith Hydro (top, right), Alstom TGL (bottom, left) and DCNS (bottom, right) (Kempener & Neumann, 2014)

#### 4.2 *Environmental Conditions*

Tidal current turbines are preferably deployed in locations with a high mean tidal current speed, such as channels, for which strong variation in current speed might be expected due to ambient turbulence, wave-current interaction, and wake effect in a tidal turbine farm. Strong turbulence will lead to large variations in power output and dynamic loads on the turbine blades, which challenges the structural design of tidal turbines.

The work and experience gained by developers testing in the European Marine Energy Centre (EMEC) tidal test site in the Falls of Warness led to the Reliable Data Acquisition Platform

for Tidal (ReDAPT) project in the UK. Between 2011 and 2014, ReDAPT characterized the flow around Alstom Ocean Energy's 1MW, DEEP-Gen IV, tidal turbine, which has a rotor diameter of about 16m and was deployed at the mid water column in 40m deep water. ReDAPT primarily used Doppler profiling to characterize the flow. Seabed mounted diverging-beam acoustic Doppler profilers (DADP) and turbine-installed (mid-depth in the water column) single-beam acoustic Doppler profilers (SB-ADP), were deployed along with acoustic and pressured based wave measurement instruments mounted the sea floor. The need to characterize the turbulence in detail led to the development of a convergent-beam acoustic Doppler profiler (C-ADP) (Sellar et al., 2015) which was also deployed during ReDAPT. The resulting ReDAPT Environmental Conditions Database (see <http://redapt.eng.ed.ac.uk>) contains approximately five hundred Gigabytes of multi-seasonal raw and processed data (Sellar et al., 2018).

As part of ReDAPT Sutherland et al. (2017) analyzed the data obtained simultaneously, during the winter months, from two ADPs separated by 78m normal to the flow direction (see Figure 4.3). The analysis shows that there were significant differences of 49% in the available power between the two locations, with strongly sheared flow resulting in velocity differences of over 1m/s between the top and bottom of the rotor plane, and a velocity change at hub height of  $\pm 0.5\text{m/s}$  resulting from the waves.

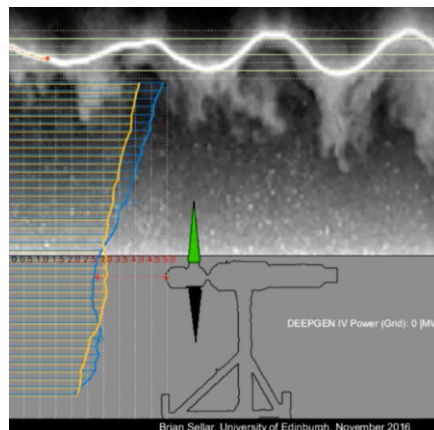


Figure 4.3: Measurements from two ADCPs deployed 78m apart by the DeepGEN IV turbine in the Falls of Warness

More field measurements of tidal currents with focus on turbulence intensity and vertical profile are needed for a better characterization of offshore sites for tidal turbine power and loads prediction. Nevertheless, the importance of velocity shear and turbulence has gained much attention by the researchers in recent years. A numerical procedure was developed by Pyakurel et al. (2017) to generate a turbulent flow field based on the input of ambient turbulence intensity and mean flow velocity, which are integrated to a time-domain code for dynamic response analysis of tidal current turbines. It is found that the standard deviations of both power and axial loads increase by 4 times if the turbulence intensity increases from 5% to 20%. Generating a target turbulence intensity in towing tank or ocean basin for model testing is extremely difficult. In Blackmore et al. (2016), an experimental campaign using static grids to generate turbulence was performed in a circulating water flume. Turbulence decays with the distance downstream of the grid and therefore different turbulence intensities can be obtained by placing the tidal turbine model at different locations from the grid. In the extreme case, turbulence has an effect on the load fluctuations experienced by the blades with a 5-fold increase.



### 4.3 Tidal turbine loads and response analysis

#### 4.3.1 Numerical methods

Similar for offshore wind turbines, numerical methods based on BEM (Blade Element Momentum) theory and CFD (Computational Fluid Dynamics) are being developed and partly validated against lab and field test results.

Due to the significant ambient turbulence and the presence of the waves, tidal turbines might be subjected to more dynamic loads as compared to offshore wind turbines. Faudot & Dahlhaug (2012) reported that wave loads are one of the main contributors to fatigue loading on turbine blades, and are a determining parameter in the calculation of turbine blade lifetime. Tatum et al. (2016) performed CFD simulations for a 10m-diameter tidal turbine in current and waves. They showed the significant fluctuations in both power and loadings, indicating the importance to consider waves in the modelling of the tidal turbines.

In many of the numerical studies, the focus was given to the overall power performance and the global loads (thrust and torque) of the turbine (Lust et al. 2013, Holst et al. 2015, Allsop et al. 2017). In some studies, detailed structural loads of the blades were obtained (Guo et al. 2017a, Barber et al. 2017).

Guo et al. (2017b) developed a BEM code for a three-blade tidal turbine in current and waves and compared both the mean and dynamic thrust and torque with the towing tank test results. A good agreement was obtained, but more validation work with respect to distributed loads along the blades should be considered. The BEM code is further used to study the blade loads in irregular waves (Guo et al. 2017a). Holst et al. (2015) performed CFD analyses of a two-blade tidal turbine using ANSYS-CFX and demonstrated the reasonably good accuracy of the CFD analysis when compared with the experimental results for both steady-state current condition and combined wave and current condition. As shown in Figure 4.4, the accuracy of the BEM code is comparable to that of the CFD analysis. Allsop et al. (2017) studied numerically a ducted, open central tidal turbine using BEM theory and an empirical model of the flow through the duct. They also show a good agreement between the BEM code and the CFD analysis for TSR (tip-speed-ratio) up to the optimal operating condition. It is also suggested that a more comprehensive validation work should be carried out. Barber et al. (2017) studied experimentally the performance of tidal turbines with adaptive pitch blades of composite material and compared it with the aluminum stiff blades. They found that the pitch-to-feather design can lead to lower blade loads, while the pitch-to-stall design has the potential of higher power generation, but also larger loads.

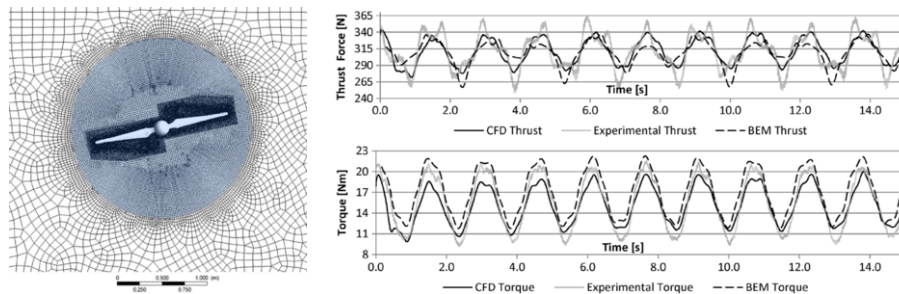


Figure 4.4: Mesh illustration for the CFD analysis of a two-blade rotor with the rotating domain highlighted in blue (left) and the comparison of the model-scale thrust and torque between BEM, CFD and measurements for a regular wave ( $H=0.25\text{m}$ ,  $T=1.883\text{s}$ , model-scale) (Holst et al., 2015)



Machine data from ReDAPT was processed by Parkinson & Collier (2016) and compared with unsteady time-domain simulations performed using DNV-GL's Tidal Bladed software. Comparisons are reported for electrical power, pitch angle and blade near-root bending moment. The analysis shows that good agreement between the simulated and measured flapwise near root-bending damage equivalent loads and load spectra. The stochastic blade load data shows significant transient loadings.

CFD methods have been extensively used to study the detailed flow characteristics of the wake of a tidal turbine in uniform and constant flow (Liu et al., 2016a), which is important to understand and predict accurately the loads on turbine blades. CFD simulations for tidal turbines in shear and turbulent flow have also been performed. Ahmed et al. (2017) performed a series of RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) CFD simulations on a 1MW tidal turbine and compared the results with the measurements from the test at the EWEC site. It was found that both RANS (with the SST  $k-\omega$  model) and LES (with the Germano-Lilly dynamic subgrid model) simulations can predict similar phase-averaged loads and blade pressures for an ideal low-turbulence case. In addition, LES simulations with realistic inflow turbulence can satisfactorily reproduce the blade bending moment spectrum as compared to the field measurements.

Combined CFD/BEM numerical methods have also been developed to study the flow through a single rotor or multiple rotors in a channel. Schluntz & Willden (2015) developed an RANS solver with an embedded BEM model to study the effect of blockage (the ratio of the rotor swept area to channel cross-sectional area) on the power performance of a single rotor in a channel. In such method, RANS simulations of the flow in channel were performed considering the forcing of the rotor obtained by a BEM model. It is then further developed to investigate the performance of a closely spaced cross-stream fence of four turbines (Vogel & Willden, 2017). The mean fence power is found to be less than that predicted for a single turbine with the same local blockage ratio, but greater than that for a single turbine based on the global blockage ratio of the fence. Similar numerical techniques were used to predict the loads on a tidal turbine with contra-rotating rotors and its support structures (Creech et al., 2017) combining LES with Actuator Line Models for the rotors, and the loads on a ducted/open center tidal turbine (Allsop et al., 2017) combining RANS and BEM models.

For design of tidal turbine blades and support structures, structural responses due to hydrodynamic loads need to be predicted. Depending on the length and the flexibility of the blades, hydro-elastic responses of a tidal turbine might be less significant as compared to aero-elastic resonant responses of wind turbine blades in turbulent wind field. Arnold et al. (2016) performed a comparative study on a 1MW tidal turbine of 13m in diameter using both decoupled and coupled CFD and structural response analysis. They found that the flexibility of the blades and main shaft of this particular turbine are of minor importance. The hydro-elastic behavior is dominated by the tower bending and the nacelle nodding properties. However, with increasing turbine size and rotor diameter, the hydro-elastic behavior may become more important to consider for blade design.

Composite materials (mainly GFRP and CFRP) are most commonly used for wind turbine blades and are also suitable for tidal turbine blades. Although environmental loads acting on wind turbines and tidal turbines are quite different, experiences and research work on composite wind turbine blades should be used when developing methods for structural design and analysis of tidal turbine blades. A tidal turbine blade design methodology was proposed by Grogan et al. (2013). It consists of a hydrodynamic analysis of the rotor using the BEM method, a structural analysis to determine the strain distribution based on a FE (Finite Element) beam model of the blade and another structural stress analysis using a detailed shell model of the blade. In the second structural analysis, stress/strain-based failure criteria of the composite layup are considered. Murray et al. (2016) developed a coupled FE-BEM design tool based on

an iterative procedure for the determination of structural (deformation and stress) and hydrodynamic (power and thrust loads) responses of the blades and applied it to a tidal turbine with passively adaptive blades. The case study on a small-scale turbine with 360mm long shows that the rotor can operate optimally at design conditions, while reducing structural loads and power capture at flow speeds larger than the design conditions due to its large flexibility.

Fibre and matrix failure and delamination are the most common failure modes of composite materials. However, it is very challenging and time-consuming to incorporate all failure modes in blade structural analysis for design. A damage-based design and analysis methodology for fibre reinforced composite tidal turbine blades were developed by Fagan et al. (2016). In particular, the Puck phenomenological failure criteria for fibre and inter-fibre failure of GFRP and CFRP were used in the FE analysis of the blades using shell elements, with the distributed hydrodynamic loads obtained from a BEM model. In another study, an advanced numerical approach was proposed (Harper & Hallett, 2015), which explicitly models the cohesive material between the composite plies and incorporates stress and fracture based failure criteria related to both damage initiation and subsequent propagation to simulate delamination. This modelling approach is validated against the experimental result of a composite test sample, as shown in Figure 4.5.

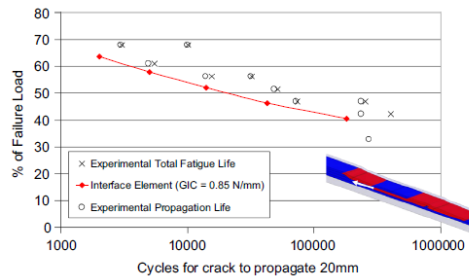


Figure 4.5 Cover ply specimen fatigue lives against normalized load level (Harper & Hallett, 2015)

Vertical axis or cross-flow tidal turbines have also been proposed and analysed. In some of the recent studies, structural response analyses of the blades and support structures were carried out using a coupled hydrodynamic/structural analysis. In the study by Wang et al. (2018), the structural analysis of an H-type three-blade vertical axis tidal turbine was performed using a beam model based on the geometric exact beam theory, which is coupled to the hydrodynamic loads analysis by a discrete vortex method. They also revealed the structural resonant responses due to the first few global vibrational modes of the support structure and the blades.

#### 4.3.2 Laboratory tests and field measurements

A number of laboratory tests (mainly in towing tanks) of scaled horizontal axis tidal turbines have been performed in the last few years. This includes testing of scaled turbines in uniform and steady flow and in addition with oscillatory motions, regular or irregular wave conditions. Normally, the integrated thrust force and the blade root bending moment are measured. In such tests, a geometrically-scaled rotor, with a scaling factor of 1:20 - 1:30 is typically used with the hydrodynamic loads scaled by the Froude law and with the tip-speed-ratio kept the same as the full-scale one. Large-scale (1:5 - 1:10) or prototype field tests are also performed, providing valuable results for numerical model validation.

An interesting comparative ‘Round Robin’ test campaign (Gaurier et al., 2015) has been conducted in two flume tanks (at IFREMER and CNR-INSEAN) and two towing tanks (at KHL

and CNR-INSEAN) under the EU FP7 MARINET program. Tests of the same three-blade tidal turbine of 700mm in diameter with constant towing speeds of 0.6-1.2m/s were performed in these four testing facilities, as shown in Figure 4.6. Time series of the torsional moment and the axial force at the turbine shaft were measured and used to calculate the power and the thrust coefficients, which are compared in Figure 4.7 in terms of mean value and standard deviation. In general, the mean power and thrust coefficients compare well and the differences for high tip-speed-ratio is mainly related to the different blockage ratio of the four tanks. Even bigger differences in standard deviations were observed for both the power and the thrust coefficients, which might be caused by the different levels of ambient turbulence in the tanks and vibrations of the towing carriages. Overall, the ratio of the standard deviation to the mean value varies from 1.5% to 5% and from 3% to 13%, for the power and the thrust coefficients, respectively.

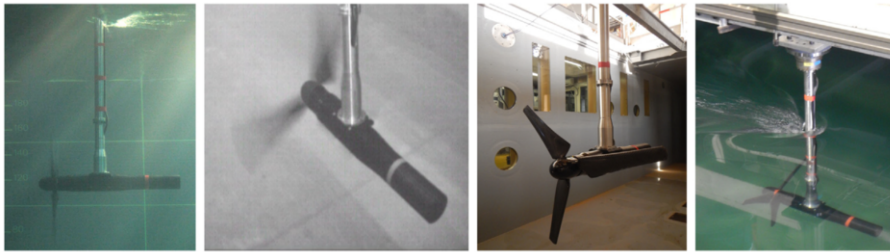


Figure 4.6 Views of the same turbine model in the IFREMER flume tank, in the KHL towing tank, in the CNR-INSEAN flume tank and in the CNR-INSEAN towing tank (from left)

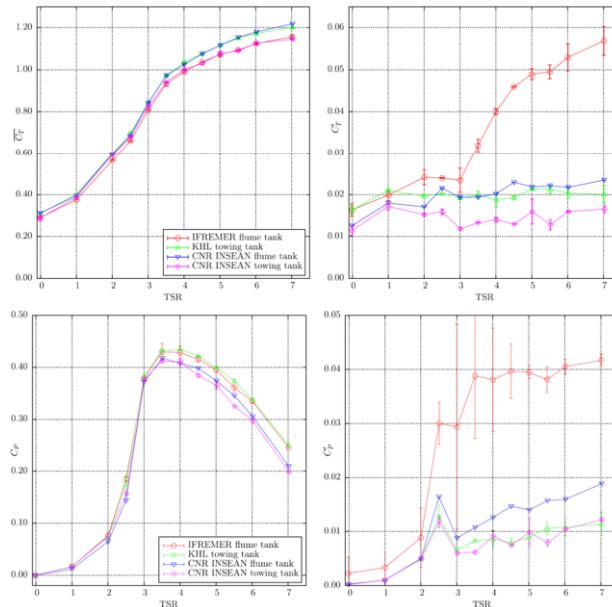


Figure 4.7 Mean (left) and standard deviation (right) of the power (top) and thrust (bottom) coefficients as function of tip-speed-ratio (TSR), obtained for every run at every tank for a mean current speed (towing speed) of 1.0m/s

Milne et al. (2013, 2015) performed model tests of a scaled tidal turbine in current with oscillatory motions to study the role of unsteadiness on the rotor loading (i.e. the blade root out-of-plane bending moment). They found that the hydrodynamic loads due to the oscillatory motions at high frequencies are in phase with acceleration, but the magnitudes are small as compared to the steady-flow loads. While, at low frequencies, the hydrodynamic loads are dominated by the dynamic inflow effect due to the oscillatory motions and a phase lead was observed. Moreover, at low tip-speed ratio, flow separation was observed, causing an increase and a phase lag in the hydrodynamic loads. They also found that the principle of superposition for turbine loads with multi-frequency oscillatory motions can be used based on the measurements from both the steady flow and the single frequency oscillatory tests, as long as the flow was attached. This is consistent with the findings by Guo et al. (2017a, 2017b), in which a model test of a scaled tidal turbine in combined current and waves was performed. A linear relationship between the wave amplitude and the turbine hydrodynamic load was observed and the superposition method can be used for turbine loads in linear irregular waves.

Most of the model tests of tidal turbines use aluminum. However, tests of composite or plastic turbines are also performed. Liu et al. (2015) performed a series of towing tank tests of a tidal turbine with a large solidity ratio and compared the performance of the metal and plastic rotors. As compared to the metal rotor, a maximum 40% decrease in the absorbed power was obtained for the plastic rotor, operating at a tip speed ratio of 3.0, which is mainly due to the high flexibility of the plastic rotor. On the other hand, Barber et al. (2017) have shown the potential to reduce the turbine loads when composite blades were used and pitched to feather for operation, based on their model test results of composite and aluminum rotors.

Field measurements of large-scale or prototypes of tidal turbines have been carried out and used to validate numerical predictions. The measurement data of the Alstom Ocean Energy's 1MW tidal turbine at the European Marine Energy Centre (EMEC) in Orkney, UK were analyzed by Parkinson & Collier (2016) and compared with the numerical simulations from the software DNV-GL Tidal Bladed. Normalized shaft power and near-root flapwise bending moment of the blade as function of the normalized inflow velocity are compared in Figure 4.8. In the numerical simulations, the onset flow turbulence is described using a von Karman velocity spectra and coherence functions. The comparison reveals a fairly good agreement between the field measurements and DNV-GL Tidal Blade, which is a BEM code.

Atcheson et al. (2015) performed a large-scale towing test in a lake for a 1:10 scale tidal turbine Evopod, which was carried by 16m long catamaran with a forward speed of 0.9-1.2m/s. The wake behind the rotor (the velocity field) was measured using Acoustic Doppler Velocimeters. The obtained maximum power coefficient is about 0.35 at a tip-speed-ratio around 3, which agrees well with the BEM prediction. A floating tidal turbine prototype GEM (Marine Electrical Generator) was developed and tested in the Venice lagoon, Italy (Coiro et al., 2017). It consists of a submerged two-hull floater, two counter-rotating ducted turbines and a tether mooring system. The field measurements of the prototype (which has a rated power of 100kW for single turbine at a current speed of 2.8m/s) indicate a maximum power of 7kW at the maximum measured current speed of 1.3m/s, which corresponds to a power coefficient of 0.6-0.65 due to the positive effect of the duct.

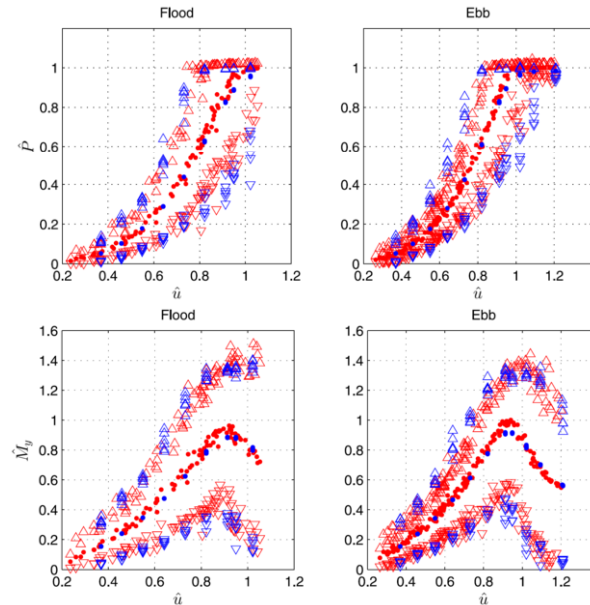


Figure 4.8 Comparison of the normalized shaft power (top) and near-root flapwise bending moment of the blade for flood (left) and ebb (right) flow conditions (Normalization performed with respect to the values at the rated condition. Max, mean, min denoted by upward pointing triangle, dot and downward pointing triangle.)

## 5. OTHER OFFSHORE RENEWABLE ENERGY TECHNOLOGIES

In addition to offshore wind, wave and marine current energy, ocean thermal energy conversion (OTEC) utilizes the temperature difference between the sea surface water and the colder, deep water to generate electricity. However, an OTEC device requires temperature differences of at least about 20 degrees Celsius to be effective (Mofor et al., 2014), which leads to the resources only applicable in the tropical waters. Moreover, a water depth of 1000m is expected to reach such level of temperature difference, which indicates a high cost for the need of extremely long pipes. A few small-scale land-based prototypes of OTEC have been built and tested, including the Okinawa Prefecture OTEC Demonstration Plant with two 50kW units in Japan (OTEC Okinawa, 2017) and the 105kW demo plant built by Makai Ocean Engineering and operated in Hawaii (Techxplore, 2017). Large-scale OTEC plants are under design and development, which includes a 16MW plant project that will be developed by Akuo Energy and DCNS in France with funding from the European Union's NER300 programme and a 10MW pilot plant that will be designed by Lockheed Martine in a project sponsored by the Reignwood Group in China (Mofor et al., 2014). In addition, MW-scale OTEC plant concepts with floating support structures (such as semi-submersible or mini-spar) have also been proposed (Stoev et al., 2017).

Similarly, a salinity gradient energy conversion plant harnesses the chemical potential due to salinity difference between freshwater and seawater, captured as pressure across a semi-permeable membrane (Mofor et al., 2014). River mouths are the most obvious locations for such resource. However, due to the high cost of membranes, this type of technology is still at a conceptual and early research and development stage. Most of the studies are conducted in labs. Only one small 4kW pilot plant was opened by Statkraft in Norway in 2009 (Statkraft, 2017), but no large-scale device exists.

Usually, commercial offshore renewable energy devices are developed with many units in a farm configuration, which occupies a large sea surface or ocean space. Combined use of ocean space for different types of offshore renewable energies and/or other sectors has become an important concern. Many research projects exist in particular in Europe and have been discussed in the previous ISSC report (Gao et al., 2015). However, as of today, there are no offshore wind farms that are combined with other use of the ocean space. It still remains to be seen how such combination is realized in actual development of commercial farms.

## **6. COST OF OFFSHORE RENEWABLE ENERGY**

### **6.1 General aspects**

Offshore renewable energy devices, such as wind turbines, wave energy converters and marine current turbines, are mainly designed to generate electricity for commercial development. In addition to being the green energy, cost of energy becomes the most important criterion for developing such technology. Since both wave energy and tidal turbine technologies are in the early stage of development, while offshore wind turbine technology has already been commercialized, we will discuss the cost issues separately. Due to the lack of industrial development, the cost estimations for wave energy converters and marine current turbines are subjected to significant uncertainties (IEA-OES, 2015). On the other hand, although some detailed data and analyses are available (Gonzalez-Rodriguez, 2017), the offshore wind industry today is a very competitive industry and therefore it is in general not easy to get the information about fabrication and installation costs of wind turbine components and operation and maintenance costs in specific wind farms. Herein, we aim for a review of the offshore wind cost from a general perspective.

Levelized Cost of Electricity or Energy (LCOE) is normally used for comparison of electricity generation cost, which is defined as the total lifetime cost divided by the total amount of electricity generated. Typically, the offshore renewable energy devices are designed with a lifetime of 25 years. The total cost consists of the capital expenditure (CAPEX) and the operational expenditure (OPEX), including the decommissioning cost. The total amount of electricity in terms of kWh is estimated or observed considering the fact that the device is not all time operational at the rated power due to the variation in the wind, wave and tidal current conditions. Typically, offshore wind turbines operate at a capacity factor (which is defined as the average generated power divided by the rated power) ranging from 40%-60%.

In addition to the LCOE, the cost of alternative sources is also a primary consideration when developing new technologies for electricity generation. The economic viability of course also depends on the prices and available capacity of electricity from alternative sources in the region being considered for offshore wind development. In the report by the US Department of the Interior and Department of Energy, Gilman et al. (2016) have considered these factors in terms of Levelized Avoided Costs of Energy (LACE). LACE is a measure of the potential revenue from electricity prices and capacity that is available to a new generator source and hence represents an estimate of the cost to generate the electricity that is displaced by a new project. The difference between LCOE and LACE indicates the net economic value. An example of the estimates was shown in Figure 6.1 for future wind farms in the US offshore regions.

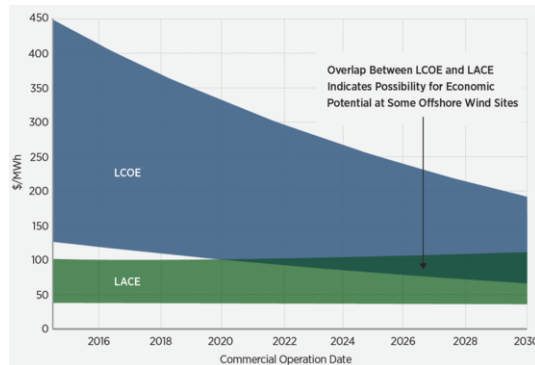


Figure 6.1: Comparison of levelized cost of energy and levelized avoided cost of energy estimates from 2015 to 2030 for future wind farms in the US offshore regions (Gilman et al., 2016)

**6.2 Current status and potential for cost reduction**

Based on the report from the Joint Research Centre, European Commission (Carlsson, 2014), Magagna & Uihlein (2015) compared the LCOE for alternative renewable energy and conventional energy technologies, as shown in Figure 6.2. The solid bars indicate the cost range as per 2015, while the shaded bars indicate the expected future cost reductions in 2050. As we can see, the LCOE of onshore wind farms is already comparable with that of the small-scale hydro power stations. The LCOE of offshore wind farms today (mainly bottom-fixed monopile wind turbines) is 12-18 Euro cent/kWh, about twice of the onshore counterpart (6.5-11 Euro cent/kWh) and potentially can be reduced to the same level by 2050. But the LCOE of both wave and tidal energy devices today is much higher than other technologies and also shows a larger scatter among the different devices. But there is a big potential for cost reduction if both technologies are commercially developed in large-scale farms.

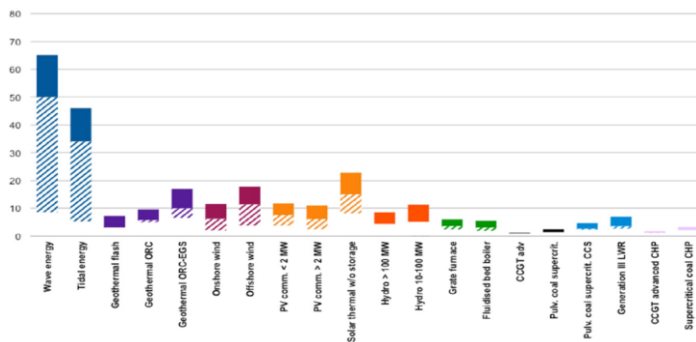


Figure 6.2: LCOE (Euro cent per kWh) for alternative renewable and conventional energy technologies (Magagna & Uihlein, 2015, reproduced based on Carlsson, 2014)

As opposite to the increasing cost in the previous years from 2005 to 2015, we have seen a clear falling trend in costs of offshore wind farms in the last two years (GWEC, 2017b). In particular in the auction for several offshore wind farms in 2016, including Borssele 3 & 4 in the Netherland, Krieger’s Flak and Vesterhav in Denmark, the bidders gave very low bids, ranging from 72 Euro/MWh to 60 Euro/MWh as shown in Figure 6.3, which is even lower

than the normal bid for onshore wind farms (Hundleby & Freeman, 2017). In 2017, Dong Energy and EnBW won the bids to build first subsidy-free offshore wind farms in the North and Baltic Seas in Germany (Offshore Wind Industry, 2017). One of the reasons for the low bids is that the offshore wind farms in auction are to be completed by 2025 at the latest. The actual development remains to be seen. But, this reflects the general trend of cost reduction in this industry, due to the improvement and maturation of the offshore wind technology and management as well as the introduction of large-scale (6-8 MW) wind turbines. Moreover, such development is in line with the overall goal for offshore wind industry by 2030, as shown in Figure 6.3.

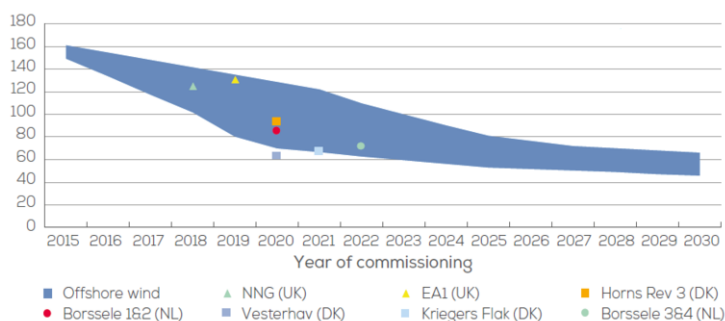


Figure 6.3: Offshore wind LCOE range and trajectory from 2015 to 2030 (Hundleby & Freeman, 2017)

The discussion above is mainly related to offshore bottom-fixed wind turbines. In terms of floating wind turbines, there are not so many turbines that are under testing out at the sea. In addition to the prototypes in Norway, Portugal, Japan and US, Statoil built the first floating wind farms in Scotland based on their Hywind technology with five 6 MW Siemens turbines, which started to operate since October 2017. The cost for developing prototype floating wind turbines is extremely high, but Statoil was able to cut the cost down in their Hywind Scotland project. They also aims for even lower LCOE at 40-60 Euro/MWh by 2030 for large-scale wind farm development (Statoil, 2017a), which will be comparable to bottom-fixed wind turbines.

The offshore wind industry needs further cut the cost down in order to provide cheaper electricity to the market by 2030. Then, it is important to understand the cost structure in today's offshore wind farms and the areas that have a potential for cost reduction. From the life cycle point of view, the cost includes CAPEX and OPEX. Typically, OPEX is about the 10-20% of the total cost. Figure 6.4 shows the CAPEX breakdown for different components and their installation for selected European farms (MAKE Consulting, 2016). As we can see, the wind turbine itself (including rotor, nacelle, gearbox and generator) accounts for 30%. The use of large-size turbines will reduce the average LCOE (Valpy & English, 2014), but probably will not reduce the cost share. The foundation cost is about 13% and could be potentially decreased. Moreover, the total installation cost is about 25%, which is an area that could be further reduced. These two areas with potential cost reduction are also relevant for the ISSC community, in terms of developing novel foundation structures and installation methods. Developing improved vessel access and condition monitoring systems are the ways to reduce the OPEX (Willow & Valpy, 2015).



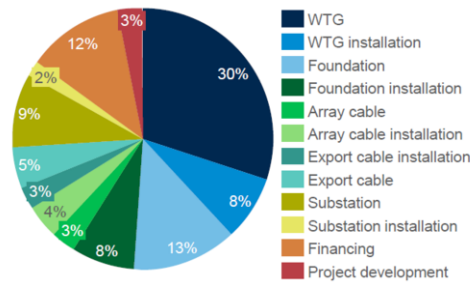


Figure 6.4: Cost breakdown for typical offshore bottom-fixed wind farms in Europe (MAKE Consulting, 2016)

It should be noted that the total cost and the cost breakdown vary significantly from project to project. In particular, an increase in water depth or distance from shore at the wind farm site would have a large impact on the cost share related to foundations and power cables (MAKE Consulting, 2016).

Most of the wave energy converter concepts today are still in the development phase with a typical Technology Readiness Level (TRL) of 5, which is defined as the technology validated (but not fully demonstrated) in relevant environment (industrially relevant environment in the case of key enabling technologies). Some leading WEC concepts have researched TRL 6 and 7, with demonstrations and prototypes at the sea, as shown in Figure 6.5 (Mofor et al., 2014). Individual large-scale tidal stream turbines have been developed and tested at sea, leading to a TRL of 7, but their performance in array needs to be demonstrated (Mofor et al., 2014). In general, the development of the wave energy sector lags that of the tidal energy (IEA-OES, 2015).

The current status about the LCOE for wave and tidal energy is available from the studies by IEA-OES (2015), Magagna & Uihlein (2015) and Astariz & Iglesias (2015). In particular, the study carried out by Astariz & Iglesias (2015) is a thorough review of all the factors that influence the LCOE of wave energy converters.

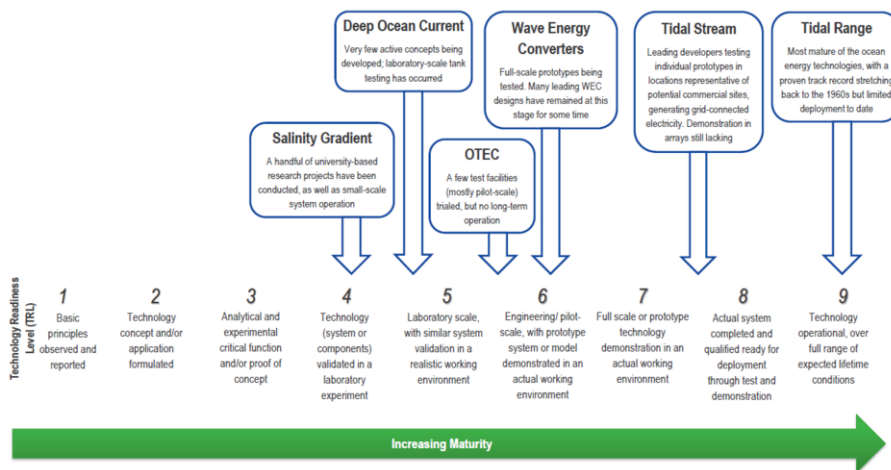


Figure 6.5: Technology Readiness Level (TRL) for ocean energy (Mofor et al., 2014)

Nevertheless, from the cost evaluation point of view, most of the analyses were based on predictions, not direct project experiences. A study (IEA-OES, 2015) was carried out by IEA Technology Collaboration Programme for Ocean Energy Systems (OES) about the LCOE of wave energy, tidal energy and Ocean Thermal Energy Conversion (OTEC) for the current stage of development and the future commercial development. It shows that the current LCOE for wave, tidal and OTEC technologies are very high, at a similar level as shown in Figure 6.2 (Magagna & Uihlein, 2015). The study also compares the cost share of different technologies. A very high OPEX share (40%) was found for tidal energy devices because of access difficulties, as compared to 14% for commercial wave energy devices and 23% for OTEC devices. The study also shows that the OTEC plants at a large scale are economically more attractive than wave and tidal energy technologies, but the geographic distribution of the OTEC resource is limited, similar to the tidal energy resource.

### **6.3 Cost models and analysis tools**

Through years, many cost models and analysis tools have been developed for offshore wind farms (Van de Pieterman et al., 2010; DNV-GL, 2017b; Kaiser & Snyder, 2013) and some for wave energy converters and tidal turbines (Chozas et al, 2014, O’Sullivan & Ardanaz, 2012).

The tools for offshore wind farm development are mainly for operation & maintenance (O&M) planning and cost analysis, with a few for installation cost analysis. Dinwoodie et al. (2015) performed a review and a benchmark study of the O&M tools, including NOWicob, University of Stavanger Offshore Wind Simulation Model, ECUME Model and Strathclyde University Offshore Wind OPEX Model. ECN has developed an Operation & Maintenance Cost Estimator (OMCE) (Van de Pieterman et al., 2010) since 2010 originally for the Dutch offshore wind industry and now becomes a standard tool for offshore wind farm developers. This tool uses data (including O&M, SCADA, load and response measurements, and condition monitoring data) and experiences gained by the wind farm under consideration and gives better estimate and control of the future O&M costs for the next 1 to 5 years. Based on the same methodology, ECN developed a tool, ECN Install 2.0 (2017), which can be used for installation cost analysis considering explicitly the effect of wind and wave conditions on offshore installation work. Based on the cost database from their projects and public information, DNV-GL recently developed an LCOE tool for offshore wind farms and used in their cost of energy modelling service (DNV-GL, 2017b). In the EERA DTOC project, a software tool, Wind & Economy (2017) was developed for optimization of offshore wind farms based on the integrated modelling of wind climate, large-scale and localized wind farm effects, electrical loss calculations and derivation of economic key figures.

In the EU FP7 research project MARINA Platform (O’Sullivan & Ardanaz, 2012), a cost evaluation tool was developed at the University College Cork and used for cost assessment and comparisons of combined offshore renewable energy devices (including combined wind/wave and combined wind/current devices). As for pure wave energy converters, an open-access tool (Chozas et al, 2014) was developed at Aalborg University for calculation of the LCOE based on the power production of a wave energy converter at a particular location. The users need to provide the power production data, which may derive from lab testing, numerical analysis or sea trials. As mentioned, due to the lack of industry experiences and data, cost evaluation for wave energy and tidal energy projects are subjected to large uncertainties. Research efforts were made to take into account such uncertainties and provide a probabilistic estimation of LCOE (Guanche et al., 2014).

The cost analysis tools are very useful for the developers to understand the cost breakdown of offshore renewable energy devices/farms and the potential areas for cost reduction. Such tools are also used for design optimization of offshore wind turbines (Ashuri et al., 2014; Martinez-Luengo et al., 2017), for minimization of the transport and installation cost (Sarker & Faiz, 2017) and the operation and maintenance cost (Sarker & Faiz, 2016; Martin et al., 2016), for

design optimization of wave energy converters (De Andres et al., 2016), for development of reference models for wave energy converters (Bull et al., 2016) and for comparison of different technologies (Castro-Santos et al., 2017).

## 7. MAIN CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

In the last three years, we have seen a promising cost reduction in some of the offshore wind farms in Europe, which brightens the future of the offshore wind industry. This is mainly driven by the use of larger wind turbines and it seems that the turbine size will continuously grow in the near future. In addition to the European market, the offshore wind markets in China and the US are also developing very fast and show big plans ahead. This provides the traditional ship and offshore oil & gas industry a great opportunity to contribute to this green technology development in many ways. For the research point of view, the professional associations like ISSC shall also contribute.

In this report, we do not explicitly deal with resources and environmental conditions that are important for design and operation of offshore wind farms. It does not mean that there is no need for more advanced environmental models or for more measurement data. Joint distribution models of wind, waves and in some cases current (established based on the long-term measurement or hindcast data) are needed for both fatigue and extreme response analysis of offshore wind turbines. This is because time-domain simulations considering the strong coupling between these environmental loads and induced-responses of offshore wind turbines (in particular floating wind turbines) are normally required for design. Distribution models that consider the turbulence intensity factor and their validations against measurement are important to consider in the future. With respect to transport, installation and operation & maintenance of offshore wind turbines, accurate weather forecast models are needed and are important for making correct decisions on the relevant marine operations. A joint effort between this committee and the technical committee on environmental conditions should be made for the next term of ISSC.

Offshore wind turbine design relies on time-domain simulations using numerical codes. In the last ten years, many codes have been developed for both bottom-fixed and floating wind turbines. There is a still strong need for validation of the codes against field measurements. IEA OC3-5 benchmark studies have been the most important research effort on the comparison of these codes and on the validation of the codes against lab and field measurement data in the recent years. ISSC members in the future should still closely follow up this study. In particular, the OC5 study now enters a critical phase that the field measurement in the Alpha Ventus wind farm in Germany with bottom-fixed wind turbines will be used for validation. Because of the difficulty to correctly measure the real wind field and to represent it in numerical simulations, comparing the statistics and/or spectra of the measured responses with the simulated ones for the same short-term environmental parameters might be the best way for code validation. It might be difficult to conduct a direct comparison of response time series and to achieve a good agreement.

In addition to the field measurements, lab measurements are still very useful for feasibility studies of novel concepts and for validation of numerical codes with respect to nonlinear environmental loads and responses. Due to the conflict between the Froude and Reynolds scaling laws, it is not possible to up-scale correctly all of the test results for a geometrically-scale wind turbine. However, the recently developed real-time hybrid testing techniques enable us to focus on specific physical phenomena for testing (for example hydrodynamic loads), while still involving other physical loads (for example wind turbine aerodynamic loads) through numerical simulations and mechanical/hydraulic/electrical actuations. Such experimental techniques still need to be proven for bottom-fixed wind turbines for which high-frequency aerodynamic loads are difficult but need to be actuated in the model test. On the other hand,

the technique for testing wind turbines in a wind tunnel with a movable foundation to simulate the effect of rigid-body motions of a floating wind turbine should be further developed.

Bottom-fixed wind turbines are well developed. However, the challenges related to coupled dynamic response analysis remain in particular for design of larger-size wind turbines with larger foundations. This includes the uncertainties in dealing with the pile-soil interaction, nonlinear wave loads on large-diameter monopile and modelling of the wind field for large rotor plane. Floating wind turbines are the focus of the wind chapter in this report. More prototypes and even more small farms of floating concepts will be built in the near future. It is still not clear at which water depth, a floating wind turbine would be more cost-effective as compared to a bottom-fixed concept. A comparative study of optimal monopile and jacket foundations for varying water depths was conducted, as a first attempt to answer this question. Mooring system design is still one of the challenges for floating wind turbines at moderate water depths (50-100m). Optimization of offshore wind turbines becomes one of the hot topics in recent years and more work needs to be done. Eventually, cost optimization (rather than just weight optimization) and system optimization (rather than just component optimization) are needed.

With respect to marine operations for the offshore wind industry, there are some research in this direction. However, more work are needed. As mentioned, special vessels for transport and installation of offshore wind turbines and supply vessels for transfer of personnel and equipment for maintenance and repair of wind turbine components need to be developed. Again, ISSC with ship specialists can certainly contribute to this direction.

Condition monitoring, maintenance and repair of wind turbine drivetrain and blades are particularly important. It is suggested that this topic can be taken in the next term of the committee together with other committees, dealing with structural health monitoring for marine structures. In the future, this ISSC committee needs to involve the specialists on wind turbine aerodynamics, blade composite materials and mechanical components such as gearbox, to cover the topics related to these wind turbine components.

Extensive research efforts have been made in the sector of wave energy conversion technology, mainly focusing on the power performance and the survivability of WECs using numerical methods, experimental techniques and to some extent, field test data. However, on the other hand, we did not witness the launching of a truly commercial-scale product during the past three years. Lack of full-scale measurement data with good quality and long duration is a general problem for this sector. More efforts in developing large-scale prototypes to gain experiences towards commercialization and to test reliability of the system in real conditions are urgently needed.

There is still no consent in the research community regarding the ideal size of WECs for commercial development. In the offshore wind industry, a clear trend of developing larger-size wind turbines for cost reduction has been observed, and it is the main driving force for the development of novel foundations and new transport/installation vessels or methods. This trend might also be applicable to tidal turbines. To some extent, MW-size WECs are needed for commercial development. However, simply scaling up the dimension of a WEC will not work. Depending on the wave resource conditions, the length of an optimal point absorber or OWC in the wave propagation direction would be about 12-20m for average northern European wave conditions. However, the width of the device, along the direction perpendicular to the wave propagation, can be optimized for a determined rated power.

A number of numerical models and tools (so-called wave-to-wire models) have been developed for global hydrodynamic loads and response analysis as well as for power performance and survivability assessment. In the past, validation of these codes were performed mainly by individual researchers or concept developers. The ongoing IEA OES benchmark study is one

of the important efforts towards WEC modelling verification and validation. A few ISSC members attended this study and some initial results were reported here. ISSC members in the next terms should be continuously involved in this study and report their findings. The effects of nonlinear waves and induced nonlinear loads on the power performance and the responses of WECs in survival conditions have also been studied, using nonlinear potential flow theory and CFD analyses. Further validation against model test results and more importantly against field measurements are needed.

Lab testing of WECs mainly focuses on the hydrodynamic performance (converting the wave kinetic energy into the kinetic energy of the primary movers of the WECs). Survivability tests and complex array tests have also been performed. Power take-off (PTO) systems for WECs should be, in principle, tested at a relatively large scale, and therefore these have to be simplified in hydrodynamic tests of the WECs. The real-time hybrid testing techniques that were developed for floating wind turbines might be interesting to pursue for testing of WECs with simulated PTO behavior.

Mooring system is one of the important components for a floating WEC concept. Studies have been performed to investigate the mooring system effect on power absorption, particularly for point absorbers. The recent work on optimization of mooring systems for cost reduction and development of active mooring lines which can result into a positive power absorption, are promising and further work is encouraged.

Tidal current turbine technology is more mature than wave energy technology. Commercial MW-size tidal current turbines have been deployed and tested. In the near future, there will be more turbines that will be tested at sea. The next stage for the leading developers of tidal turbines is to deploy multiple turbines in a small array for testing.

The measurements at the test sites show significant variations of current speed in time and along the vertical profile. Moreover, the wave-current interaction adds the complexity in the velocity field which significantly influences the dynamic loads on turbine blades. Site measurements with sufficiently long duration are still needed.

Numerical codes based on BEM or CFD have been developed and used to predict hydrodynamic loads on tidal current turbines. Most of the codes are only validated against lab test results. Validation against field measurements is generally lacking or not available to the public. More efforts should be made in this direction. In particular, uncertainties in the field measurements of current conditions and tidal turbine performance and responses need to be well treated for numerical code validation. Numerical codes that can capture structural responses for design are also needed.

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