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COMMITTEE V.4

OFFSHORE RENEWABLE ENERGY

COMMITTEE MANDATE

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

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1. DISCUSSION

1.1 Official Discussion by David M. Ingram

1.1.1 Introduction

The report describes the state of the art and research landscape in offshore renewable energy in 2015. It is divided into sections dealing with floating offshore wind, wave energy, tidal energy and multi-use platforms respectively. Whilst useful this sectionalisation fails to draw out and highlight many of the important and common issues facing the sector. For future reports a thematic approach may be better.

The committee's mandate is 'Concern for load analysis and structural design of offshore renewable energy devices. Attention shall be given to the interaction between the load and structural response of fixed and floating installations taking due consideration of the stochastic nature of the ocean environment. Aspects related to prototype testing and certification shall be considered.'

To fully understand the fatigue loadings and survivability conditions for marine energy converters their design, working environment and mooring configuration need to be comprehensively understood. This tends to lead to the report losing focus in some areas.

1.1.2 Remarks on specific areas in the report

– *Resource Assessment*

The EquiMar project produced both high-level descriptive protocols and more detailed procedures [1]. Care must be taken when reporting marine energy resources and in comparing assessments, it is useful to distinguish between

- Theoretical resource: A top level statement of the energy contained in the entire marine resource.
- Technical resource: The proportion of the theoretical resource that can be exploited using existing technology options.
- Practical resource: The proportion of the technical resource that can be exploited after consideration of external constraints (e.g. grid accessibility, competing use (shipping lanes, etc., environmental sensitivity)

Many assessments, particularly for wave energy are simply based on the average wave power-per-meter crest rather than considering the specific power performance of the machine (in varying sea states) being deployed. This leads to significant over predictions of the net energy yield. Methods for the assessment of resource are discussed in EquiMar protocol 1A and also in the assessment of field data from sea trials 2B. These techniques have been incorporated into the IEC technical specifications on the power performance of wave [2] and tidal [3] energy converters.

It is therefore critical in these assessments and those for offshore wind to distinguish between the high level theoretical resource and more specific technical and practical resources which account for the limitations of technologies to convert the raw energy and on restrictions on placement such as packing density for maintenance operations and marine spatial planning considerations.

Work on combined wind/wave resource assessment in European waters from just south west of the Canary Islands to just north of Trondheim (also including the Mediterranean and Black Seas) were constructed by the EU FP7 Marina-Platform project using 10 years of hindcast data created using the SKIRON model by NKUA. In this reanalysis of atmospheric and wave fields was be performed with state of the art tools (LAPS, SKIRON, RAMS, WAM4). Providing, for the first time, wind speed and turbulence, calculated dynamically at the turbines hub height (40 or 60 m ASL) with co-located wave climate information providing spatiotemporal distributions of the resource at a level of accuracy and detail far beyond the existing W2 atlases. The resulting model predictions were compared with wave buoy data [4, 5] showing good agreement but with some discrepancies where waves are reflected from the coastline or strongly diffracted.

This point to the need for the inclusion of near-shore spectral wave models (e.g. SWAN) in the generation of datasets of this type.

One of the most critical sites for tidal ow in the UK is the Pentland Firth where the EMEC test site is located, there have been a number of studies of the ow in the falls of warness including modelling where surface radar measurements were hybridised with a shallow water model produced using the open source suntans software, it is a shame that this work and that assessments for the sound of Islay or Strangford Narrows are not discussed especially as tidal turbines are being deployed in these locations.

ADCP measurements have shown that in highly tidal environments the flow is very three dimensional. This means that the assumptions in 2D and layered shallow water models (even with Boussinesq assumptions for velocity profiles) are of limited applicability. ADCP campaigns have been conducted around tidal turbines and in highly tidal environments (e.g. ReDAPT project) with some development of new instruments (e.g. convergent beam ADCPs [6]) in an attempt to overcome the limitations of the oceanographic instruments in highly tidal environments. This work has also highlighted the importance of both large scale turbulent structures and waves on the a-harmonic loading experienced by tidal energy converters. This is further exacerbated by the nonlinear interaction of strong currents and waves which can lead to steeper higher waves [7].

– *Offshore wind*

  o *Fixed wind turbines*

The key challenge currently for fixed wind turbines lies in the area of operations and maintenance costs, new vessels and experience with installation techniques has done a lot to reduce CAPEX costs for turbines (particularly with the move to large and larger turbines) but OPEX costs remain persistently high. Moving farms in the North Sea further offshore (c.f. UK Round 3 sites) leads to long service journeys from ports. This is leading to the development of offshore service hubs and accommodation modules. In the recent FP7 TROPOS project on multi-use offshore platforms the most economically promising finding was the offshore service hub for wind turbines. It is possible that offshore service modules could be adopted from existing Oil and Gas technology.

  o *Floating wind turbines*

Recent work has investigated the effect of wind force induced tilt on the hydrodynamics of a semi-sub, the results show that the RAOs can be significantly affected by small tilt angles and the performance of the heave plates is affected [8]. In addition to other considerations the modified motions have implications for the mooring arrangement of the platform.

The dynamic performance must also be taken into account in the mechanical design of the gearbox and turbine. Work on such integrated design was performed as part of the EC MARINA Platform project.

A demonstration project by Mitsubishi Heavy Industries is currently underway which makes use of a variable hydraulic transmission as an alternative to mechanical gear- boxes. Land based demonstration of a 7MW turbine is underway in Scotland at the Hunterston win turbine test site and one of the 7MW SeaAngle turbines to be installed in Fukushima (Japan) will also use this drivetrain. The developer of the drive-train, Artermis Intelligent Power was awarded the 2015 MacRobert Award - the UK's premier award for engineering achievement.

The French Vertiwind project (including EDF, DCNS and Technip) is designing a semi sub based vertical wind turbine for deployment in the Gulf of Lyon. The turbine has been demonstrated on shore and coupled aero-hydrodynamic analysis has been performed.

It should be noted that wave basin tests of floating HAWT systems have been performed using an actuator disk subjected to loading by a controlled fan, for a complete simulation a motorised rotating set of blades is needed so the system has the correct angular momentum characteristics. Force measurements from the actuator disk care used to control the fan. The system can be used to model the aerodynamic performance of the turbine very effectively. An alternative is to use a ducted fan mounted in the turbine nacelle to generate wind force to mimic the thrust forces on the turbine tower. Such systems may also need a rotating mass to provide the correct angular momentum.

  o *Transport, installation, operation and maintenance*

The EU LeanWind project is considering methods for improving these aspects. Modelling of CAPEX and OPEX costs for floating wind systems was considered in MARINA Platform and for hybrid systems in TROPOS. Weather windows for operation are particularly critical to achieving strong cost reductions and this relies on many of the resource assessment tools referred to in x2.1.

– *Wave energy*

Work on wave energy conversion technologies started in the mid-1970s with the pioneering work of Salter (Scotland), Whittaker (Norther Ireland), Matsuda (Japan), Falcao (Portugal), Falnes (Norway) etc. Much of this work stalled when the oil price reduced and the significant engineering challenges could not be overcome in a cost effective manner. Early work included both standard and backward bent duct OWC, the Edinburgh duck (which later used a digitally controlled hydraulic PTO -further developed by Artemis Intelligent Power and now applied to wind turbines), and heaving and surging buoys (with latching control).

Ocean Energy Europe was not established by the European Commission, it formed as a trade association, initially with academic and industrial members (as the European Ocean Energy Association - EUOEA) and recently changed its name, Whilst the wave energy taxonomy due to Falcao is useful a more flexible system was introduced by EquiMar where devices are classified according to the type of prime mover and the point of reference (e.g. buoyancy-buoyancy devices which are articulated like Pelamis, or seabed inertia devices like Oyster and the Wave Roller) [1].

Slender bodies can be analysed using a strip-theory approximation, which allows limited non-linear hydrodynamics to be computed efficiently. This approach has been used by PELAMIS to model their machine, the resulting set of PELS tools can be used to optimise the stiffness, damping and spring settings of the PTO system to maximise energy. The tool could be run using linear or non-linear hydrodynamics with much smaller run times than that for CFD. It is important to note that the PTO of devices such as PELAMIS and OYSTER (and indeed the Edinburgh duck) must be controlled to optimise wave energy capture; these systems do not use latching as a control mechanism.

General purpose wave-to-wire models have also been created which operate in the time-domain using a state space representation of the device. These models use frequency domain parameters computed with a linear hydrodynamics code like WAMIT and model the complete power train e.g. [9, 10]. These codes can handle a very high number of degrees of freedom with reasonable efficiency and have also been used to optimise control settings. Nambiar et al [9] also showed, using the same approach, that transient effects in the electrical network directly affect the hydrodynamics of a small array of heaving buoys, applying their model to WaveStar as part of the SDWED project. McCabe et al [11] have applied the method to optimise the shape of a WEC for different sea states. T Such tools allow a large number of sea states to be analysed to determine the optimum control settings. It is however important to note that non-linearities due to steep waves have an important effect on the power production of many devices and not only on the ultimate limit states and survivability.

There has been some consideration of the optimal layout of wave farms where careful positioning of WECs within the array can enhance production by trying to ensure that waves radiated by one device are in phase with the motions of the other devices. Commercial tools like DNV GL WaveFarmer are being developed to assist in the layout of wave farms.

Ongoing work within the Wave Energy Converter Arrays Network (WECAN) is looking at the use of Kochin functions to represent WECs within spectral wave models, to allow their integration into tool sets like DHIs MIKE21 [12, 13]. This has identified the key factors that distinguish the fundamental hydrodynamics of heaving and surging/pitching wave energy converters and validated a spectral-domain model of an OWC wave energy converter based on wave-tank experiments. Understanding the key factors that distinguish heaving and surging/pitching wave energy converters will have a significant impact on the development of wave energy as it will help to avoid the misappropriation of design principles between devices operating in different degrees of freedom. The WECAN group have also been involved in the experimental testing of a very large array of wave energy converters [14].

The IEC TC114 have a project team working on standards for tank testing to complement those developed by the ITTC and the work reported by the EquiMar project and being further developed by MARINET. In Addition to the DNV procedures for certification IEC TC114 is working on a technical specification on design and conformity, work has also been undertaken by Bureau Veritas as part of the EU Marina Platform and TROPOS projects. The testing guides and works in EquiMar and Marinet presents a pathway which includes small and large scale tank tests and small and full scale prototype deployments in the marine environment.

There are also a number of national initiatives aimed at harmonising development of WECs. For example, Wave Energy Scotland has launched a funded programme for the development of a PTO system which could be applied to a number of different technologies. They will have programmes for new devices, moorings etc. with the aim of further developing the sector. Wave Energy Scotland was established following the collapse of Pelamis wave power (perhaps the leading developer) when changes in the UK electricity market highlighted the fact that all devices were at too lower technology readiness level to be supported by commercial project developers or utilities.

When the 62600-1 (Terminology) PT team discussed the rated power of a wave machine we concluded that the name plate rated power could only be that declared by the manufacturer [15]. The stochastic nature of waves means machines have to be sized for very energetic sea states which may only occur 5-10% of the time, the average power production of the machine will be much lower. This leads to the principal that machines should be rated using an occurrence matrix of sea states, characterised by Hm0 and Tp, so the average annual production is stated.

– *Tidal current energy*

In the introduction it should be noted that horizontal tidal turbines have now supplied in excess of 10TWh of electricity into the grid. The 1.2MW (twin 600 KW rotor) SeaGen system in Strangford Narrows, Northern Ireland, UK is responsible for most of this. There have been a number of acquisitions by large enterprises (including Andritz and Voith) of HATT technologies, while work is in progress to develop the first tidal farms by Maygen (Inner Sound, Pentland Firth, Scotland), DP Energy (Fair Head, Norther Ireland) and EDF (Cap Brezhat, Brittany, France). This demonstrates the relative maturity of the technology compared to the floating wind and wave.

A recent analysis of composite blades in sea water conducted by Strathclyde University, as part of a tribology research project within UKCMER, has shown the sea water intrusion into cracks leads to accelerated delimitation and failure of composite blades. There is ongoing work within the UK Centre for Marine Energy Research at the universities of Swansea, Cardiff, Cranfield, Cambridge and Durham on the reliability of turbine power trains resulting from turbulent fluctuations and wave loading on the rotors.

In the field turbines are exposed to wave loading from many directions with the current leading both to changes in wave length and to amplification of the wave height [7]. The need to assess this experimentally has led to the development of the FloWave Ocean Energy Research Facility in Edinburgh. A unique 25m diameter circular wave basin which is able to combine tidal currents with waves from any relative direction [16]. Various techniques for embedding model turbines in ow simulations have been adopted from the wind sector. In addition to simple actuator disks, coupled blade element momentum theory actuator disks (or Hydrofoil Element Actuator Disks, HEAD) models and coupled blade element momentum theory actuator line (Hydrofoil Element Actuator Line, HEAL) models have been used. In both the HEAD and HEAL models torque control had been used to determine the rotor speed [17, 18, 19]. As part of the ETI PerAWaT project DNV GL developed TideFarmer an array layout tool based on Gaussian wake models. CFD models using HEAD/HEAL approaches have been used as part of the PerAWaT and NERC FLOWBEC projects [20, 21].

o *Experimental testing*

The use of redesigned scale rotors to provide the same distributions of thrust (CT) and power (CP) with tip-speed ratio is well established for the aerodynamic testing of rotors in wind tunnels and has been extended to the testing of small scale tidal rotors [22] in flumes, flowing water basins and towing tanks (e.g. [23]). Such model tests have been shown to provide good comparisons with predictions from both 3D CFD simulations of rotors and blade element momentum theory predictions.

A 1.2m model scale turbine was tested in the facility in 2015 as part of the UKs XMED project. Further tests in co- and counter- propagating waves in current were performed in the IFREMER flume [24].

– *Multi-use systems*

In terms of combined use of the sea the MARINA Platform project developed a GIS tool based on 10 years of meteorology hind-casting with collocated wind, wave and tidal data [25, 26]. This tool was used to develop a LCOE based site selection metric and has been extended for use in the TROPOS and LEANWIND projects for site selection. It follows the approach taken in ORECCA but at a much finer level of detail. A detailed comparison between the wave-rider buoy measurements and the met-ocean predictions has been made (see [4, 5]).

1.1.3 Conclusions

I wish to congratulate the committee on the breadth and scope of their analysis; I hope the above comments will be useful. In terms of further work I would recommend the following:

Increased distances from shore coupled to highly energetic sea states (often in remote areas) mean that, for all technologies: installation, operations and maintenance are very expensive (often dominating the levelised cost of energy) and weather windows for access can be very poor. This "perfect storm" can only be addressed by developing robust technologies which are able to be rapidly deployed and removed for service, or accessed safely, using small work boats. To do this new light weight, robust, modular, power trains must be developed to reduce maintenance intervals so far as is reasonably practicable. Another key impact on the cost of a project is the cost of the mooring system. If lightweight mooring systems can be developed massive savings accrue, both in terms of the cost of the mooring system and the cost of the vessels needed to deploy and maintain it.

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1.2 Floor and Written Discussions

1.2.1 Xiangyuan Zheng

1. Earthquake load needs to be included with heavy weight in the Environmental Loads, considering its significance in pan-pacific countries. So far undersea seismic ground motions have not been used in earthquake analysis and we still have to reply on land records. But, it is dangerous to assume that land and undersea ground motions are of the same characteristics.
2. Health monitoring of fixed bottom offshore wind turbines should be urgently carried out, with simultaneous measurement of metocean conditions. This is not only useful for identifying the structural properties and for the life-cycle assessment of structures, but also helpful for the ongoing development of floating offshore wind turbines.

1.2.2 Lyudmil Stoev

Is there any particular reason OTEC (Ocean Thermal Energy Conversion) technology to not be covered in ISSC2015 ORE Committee report since it was covered in ISSC2012?

H2S (Hydrogen Sulfide) resolved in sea water as a source of renewable energy was also not covered. Future R&D on Energy from H2S could be based on existing OTEC structures and thus it is of special interest to me.

1.2.3 Feargal Brennan

I am grateful to the committee for its extensive report and to the chairman for communicating this effectively. My comments echo those made by the official discusser in his observations concerning the separate treatment of Marine and Offshore Wind Renewable Energy. There is a danger in trying to cover all technologies in this sector irrespective of their maturity, as focus on the current pertinent challenges might be diluted and give a wrong impression of the challenges facing those concerned with Offshore Renewable Energy today. I refer in particular to the relatively large developments for offshore wind in Europe; at the time of writing 10.4GW of Offshore Wind energy installed and operating (50% of this in UK waters) with a further 2GW in construction/planning representing an investment of Eur10bn in 2016. There have been several high-profile commercial litigation cases related to disputes and the adequacy or otherwise of certification authority guidance for the design of offshore wind support structures in the committee's reporting period (Greater Gabbard being the most well-known, reference can be found by searching for "Greater Gabbard Dispute"). DnV guidelines for grouted connections of transition pieces have had to be revised and there have been other important updates including concerning the treatment of inner compartments as "air-tight" for the purposes of corrosion fatigue considerations. I suggest that the new committee might focus on certain areas concerned with structural matters that cut-across all Offshore Renewable Energy Technologies so that some of these can be explored in greater depth.

In addition there have been a number of large Joint Industry Projects initiated and will be coming to an end during the period of the 2015-2018 committee e.g. Offshore Wind Structural Lifecycle Industry Collaboration (SLIC) Joint Industry Project (JIP), the background of which can be read in the reference (Brennan & Tavares, 2014).

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1.2.4 Kim Branner

First, I will like to congratulate the committee on the comprehensive report. You show in Figure 4 in the report that capital cost (EUR/W) is increasing for newer offshore wind farms. As you correctly state reducing the cost of energy (CoE) is a major challenge for offshore wind energy and I believe it may be a game stopper if we do not soon see an actual reduction of CoE.

I will like to hear the recommendation from the committee on what you see as the way forward to obtain a significant reduction of CoE. You have reviewed many papers. Is there anything that seems promising in order to reduce CoE significantly? And in which areas do you recommend further research as most important in order to reduce CoE?

Finally, I will like to suggest that attention to reduction of the cost of energy is added to the mandate of the 2018 committee.

1.2.5 Iraklis Lazakis

A few references that would be useful on the O&M front for the upcoming committee are listed below. Moreover, realising that there are lots of new developments on O&M modelling, I would suggest the initiation of a benchmark study for a number of O&M tools developed by both industry and academia.

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1.2.6 Tomoaki Utsunomiya

Congratulations for the excellent and comprehensive report on offshore renewable energy. I would like to make a few comment on the cost of floating wind.

The committee has reported that the Cost of Energy (COE) (of floating wind turbines) is much higher than that of offshore bottom-fixed wind turbines, due to costly support structures. It would be true considering the fact that the floating wind turbines are now in the development phase. However, in near future, I may be expected that the COE of floating wind turbines reduces significantly due to mass production of the devices and possibly easier installation than the bottom-fixed types. In fact, Carbon Trust's report on 'Floating Offshore Wind: Market and Technology Review' (June 2015) estimates that LCOE (Levelised Cost of Energy) of floating wind can reach cost parity with bottom-fixed offshore wind by the end of 2020s.

2. REPLY BY THE COMMITTEE

2.1 Reply to Official Discussion

The committee highly appreciates Prof. David M. Ingram's careful review of our report, providing us valuable comments on each chapter, in particular on resource assessment and tidal turbines, and suggestions for the next committee.

Prof. Ingram has not directly raised many questions concerning our report. Instead, he kindly provided additional important literatures (in total 26 references), which are complementary to those included in our report. This will help to give a full picture of the recent development of the wind, wave and tidal energy technologies. The readers are recommended to look at these references as well when reading our report.

Regarding the sectionalisation of our report, he suggested a thematic report structure rather than the one we used based on different technologies (wind, wave and tidal), in order to highlight the important common issues facing this sector. We agree with Prof. Ingram that it is important to address in particular by the research community like ISSC the common challenges in this area. Doing so would be beneficial to the development of the whole sector since these technologies are relatively young and there are many problems need to be solved. However, the different development stages of the three technologies make it difficult to categorize and address all of the common issues. What we can foresee is that the experiences gained from and the technologies developed in the offshore wind industry would be very valuable for the future development of the less mature wave and tidal energy technologies. It is the same idea that this committee on offshore renewable energy was introduced to ISSC in 2006 since the technologies developed in the mature offshore oil & gas and maritime industry could be transferred to the area of offshore renewable energy. In particular, the technical committees in ISSC are organized by subjects and disciplines and the new research findings and technological developments summarized by these committees would be very useful for our committee with potential applications to offshore renewable energy.

Prof. Ingram's specific comments were made on chapter by chapter, therefore our responses to his discussion will follow the same order, with some topics discussed in more details than others.

– *Resource Assessment*

Prof. Ingram emphasized the importance to distinguish between the theoretical, technical and practical values when assessing offshore renewable energy resources. We fully agree with this comment. In our report, this part was not clearly written. Actually, it is the annual mean wind speed (Figures 1-2 in our report) and the annual mean wave power (Figure 3) with a geographical distribution that were presented. This only can be considered as an indicator of the available theoretical wind and wave energy resources and their distributions. A better resource assessment should be site- and concept-specific. This can be done by combining for example a long-term distribution of hourly mean wind speed with the power curve of a wind turbine, or a long-term joint distribution of significant wave height and spectral peak period with the power matrix of a wave energy converter, to obtain the annual average power output.

Prof. Ingram also provided additional information about the EU FP7 MARINA Platform project (http://www.marina-platform.info/) in which assessment of combined wind and wave energy resources at a high level of accuracy and detail have been carried out. These assessments are particularly important for the development of multi-use platforms (such as combined wind and wave energy devices). Prof. Ingram also critically pointed out the lack of discussion on tidal energy resource assessment for several locations in UK where tidal turbines are being deployed. A few references on this topic were provided. The committee highly appreciates this additional information.

Since the ISSC Technical Committee I.1 Environment dedicatedly addresses the issues related to environmental conditions for all kinds of offshore structures in the ocean space, we suggest that, the next committee should cooperate with the Committee I.1 on resource assessment. Other topics such as design environmental conditions and short-term weather forecasting for marine operations (for example transportation and installation of offshore wind turbines) can also be dealt with.

– *Offshore wind*

Prof. Ingram's comments on the offshore wind chapter are mainly related to floating wind turbines for which novel concepts (for example with a hydraulic transmission or with a vertical axis rotor configuration) have been proposed to reduce the negative effect of high centre of gravity with geared drivetrains and horizontal axis turbines for floating applications. Examples of such new developments were provided by Prof. Ingram. In our report, vertical axis wind turbines have been discussed. Regarding wind turbine drivetrains, the focus of our report was on gearbox, which represents the majority of drivetrain systems in the commercial wind farms today. However, experiences from onland wind industry show that the downtime induced by repair or replacement of gearbox is significant and the reliability of such systems should be improved in particular for offshore applications. Therefore, the development of other type of drivetrains such as hydraulic transmission or direct drive is interesting and the next committee can look at these concepts.

Prof. Ingram also commented on the experimental techniques for testing of floating wind turbines in labs (towing tanks or ocean basins). This topic was discussed in detail in our report, with the main references to a series of tests (Fowler et al., 2013, De Ridder et al., 2014) on spar, semi-sub and TLP floating wind turbines that were carried out at MARIN, the Netherlands. The difficulty still lies in rotor scaling and wind field generation. Therefore, when the purpose of a test is to study the motion behaviour of a floating wind turbine concept under the simultaneous wind and wave excitations, one just needs to represent the total integrated loads on the entire rotor using a disk with drag-type loading (Roddier et al., 2010) or a speed-controlled fan (Azcona et al., 2014). If the tests are used to validate numerical models, a better strategy is to create a numerical model based on the model-scale dimensions and to compare the numerical results directly to those measured from the tests, in order to avoid the effect of the distortion in scaling of the viscous loads.

Prof. Ingram also stated that for bottom-fixed wind turbines, cost reduction is of utmost importance and the focus now should be to reduce OPEX since there have been a lot of work already done on reducing CAPEX. The committee agrees that OPEX becomes a very important part of the total cost when offshore wind farms move farther from shore. It should be reduced on one hand by increasing the reliability of wind turbine components and therefore reducing the time interval for repair or replacement, and on the other hand by providing means (for example offshore service hubs and accommodation modules as Prof. Ingram mentioned) for easy access to individual turbines when maintenance or repair is necessary. We suggest that the next committee should spend more efforts on the operation and maintenance issues.

However, the committee also believes that CAPEX can be further cut down by better and efficient offshore installation. Offshore wind turbines today are installed by jack-ups with large crane capacity, which usually serve for the offshore oil and gas industry with a high daily renting rate. Purpose-built vessels for installing offshore wind turbine components (foundation, tower and rotor) are being developed and should be more used in this industry. Secondly, accurate numerical predictions about the operability (weather window) of installation vessels should be developed and can be used to reduce the uncertainties in installation planning and execution. Typically, there are in the order of 80-100 units in a commercial offshore wind farm and efficient logistics for transportation and installation of turbine components are crucial for reducing the CAPEX. These topics can also be investigated by the next committee.

– *Wave energy*

Prof. Ingram provided the information about the PEL tool that was used to analyse the Pelamis concept and that can include the nonlinear mechanical feature of the power take-off (PTO) system when running its time-domain module. We also agree with his argument about the use of frequency-domain hydrodynamic and motion analyses for example for optimization of the damping and stiffness settings of a PTO system due to its high computational efficiency.

Prof. Ingram also commented on the hydrodynamic modelling of wave energy converters (WECs). He pointed out the importance of nonlinear hydrodynamics not only for survivability analysis in extreme conditions but also for power performance analysis in operational conditions. We fully agree with his comment. In particular, it is important to consider nonlinear hydrostatic restoring and Froude-Krylov forces for point absorbers with a relatively small displacement. In addition, the nonlinearity due to large motions of this type of WECs should also be considered and it has an effect on power absorption. This is consistent with the findings from Rogne (2014), which were discussed in our report. Prof. Ingram also provided the information about the general purpose wave-to-wire models and commented on their advantages to include nonlinear hydrodynamics and advanced control. We appreciate these comments.

Our report discussed the topic on wave farm analysis, and we appreciates the additional information provided by Prof. Ingram about the DNV GL tool WaveFarmer for optimal layout of wave farms and the ongoing work within WECAN (Wave Energy Converter Array Network).

Prof. Ingram also discussed a very important aspect for developing wave energy technology. That is to harmonize the development of WECs by standardizing the components (for example PTO systems, moorings, etc.) that can be used for a number of different WEC technologies. He provided the information about the programme funded by Wave Energy Scotland. These aspects were not discussed in our report and should be addressed by the next committee.

Prof. Ingram also pointed out that the use of the terminology, rated power, is not adequate to specify the power performance of a wave energy converter since the ratio between the maximum power output (which sizes the PTO system) to the average power production is normally very large, in the order of 5-10. The annual average power production based on specific site conditions should be characterised. We agree with this comment.

– *Tidal current energy*

Regarding the tidal turbine technology, Prof. Ingram has kindly provided the information about many ongoing research projects and field developments of horizontal axis tidal turbines. He pointed out that the total electricity generated from tidal turbines (which is mainly from the 1.2 MW SeaGen twin rotor system in the Strangford Narrows, UK) reaches 10 TWh. He also indicated that the tidal turbine technology is relatively mature as compared to the wave and floating wind energy technology. We agree with Prof. Ingram that the tidal turbine technology is very likely to be the second one that will be commercialized after the success of offshore wind turbines. We also foresee that commercial floating wind turbines will be soon deployed in deep waters in Japan and US. While, there are still a long way to develop commercial wave energy converters. However, deploying tidal turbines still faces many challenges particularly related to installation, operation and maintenance.

In our report, there are limited discussions on modelling and analysis of tidal turbines. Due to the similarity between horizontal axis wind turbines and tidal turbines, theoretical, numerical and experimental methods developed for wind turbines can be and have been well adopted to model and analyse tidal turbines. We appreciate the information from Prof. Ingram on these topics.

Prof. Ingram emphasized the challenge on the combined effect of current and wave loads and induced fatigue problem for tidal turbine blades. Prof. Ingram introduced the FloWave lab at the University of Edinburgh, which is designed to combine tidal currents with waves from any relative direction and is ideal for testing of renewable energy devices under simultaneous current and wave loads. We also think that advanced experimental facilities and techniques are important steps to reduce the uncertainties in the development of offshore renewable energy technology.

Prof. Ingram also cited a recent work that revealed a fatigue problem in the structural design of composite rotor blades and mentioned that more research efforts are being made to increase the reliability of tidal turbine structures and power trains. We also think that rational structural design with respect to ultimate and fatigue limit states is an important aspect for developing reliable and sustainable offshore renewable energy technologies. Most of the previous research projects in particular on wave energy have been focusing on only hydrodynamic performance and power absorption of devices, with less attention on structural design for extreme conditions, leading to unexpected failures. The committee is happy to see that there are more research efforts on extreme and fatigue response analysis and design for offshore renewable energy devices.

2.2 Reply to Floor and Written Discussions

2.2.1 Xiangyuan Zheng

Prof. Xiangyuan Zheng asked two questions, one on seismic load analysis for offshore wind turbines and the other on health monitoring.

The committee agrees with Prof. Zheng that, for earthquake prone areas, seismic loads should be taken into account in the design of offshore wind turbines. It is particularly important for bottom-fixed offshore wind turbines because the ground motions due to earthquake might induce a significant dynamic effect on structural responses of the wind turbine system. However, it would be less important for floating wind turbines because of mooring systems. In such seismic load analysis, the ground motions typically based on the records of the previous earthquake events are important inputs. We agree with Prof. Zheng that there are different characteristics of onland and offshore ground motions due to earthquake and it might be non-conservative to use onland records for design of offshore wind turbines. Recently, Chen et al. (2015) compared the onland and offshore ground motions recorded in the K-net project in Japan and in the SEMS project in California, US. They found that the horizontal ground motions offshore have a larger characteristic period (0.5-0.6 s) than those onland (0.2-0.3 s). This indicates different responses and therefore structural designs when using these ground motion records as input for design analysis. However, detailed analysis of seismic data is beyond the mandate of this committee and we suggest Prof. Zheng to contact the members in ISSC Committee I.1 Environment for further information on seismic data.

Health monitoring or condition monitoring (CM) is one of the important and hot topics for cost-effective operation and maintenance of offshore wind turbines. In the onland wind industry, CM has been employed for the early detection of faults/failures in structural components of wind turbines (such as blades and tower) and mechanical components (such as gearbox) based on techniques including vibration analysis, acoustics, oil analysis, strain measurement and thermography. Garcia Marquez et al. (2012) provides a good review of the start-of-the-art on the CM with focus on land-based wind turbines. The same monitoring techniques might be used for wind turbine components in the offshore environment. For CM of support structures, the experiences from the offshore oil & gas industry can be helpful. In a study (HSE, 2009) on structural integrity monitoring for offshore structures (both bottom-fixed and floating) funded by the Health and Safety Executive (HSE), UK, current CM technologies were reviewed and compared, with focus on acoustic emission monitoring, air gap monitoring, strain monitoring, fatigue crack detection, leak detection, riser and anchor chain monitoring, etc. One of the challenges is to detect local structural damages sufficiently earlier before they develop into a catastrophic failure. Therefore, inspection instead of condition monitoring is often used for structural components in offshore platforms. While for machinery components, CM technologies are widely applied. The committee agrees with Prof. Zheng that it would be beneficial to apply the CM technologies in the offshore wind industry. However, the complexity of response characteristics of offshore wind turbines under simultaneous wind and wave loads imposes a big challenge for the successful application of the current CM technologies. More research efforts should be made in the direction to increase the effectiveness and the reliability of the CM technologies.

2.2.2 Lyudmil Stoev

The committee thanks Mr. Lyudmil Stoev for mentioning other types of offshore renewable energies, such as ocean thermal energy. As indicated by Lyudmil, the OTEC (Ocean Thermal Energy Conversion) technology was discussed in the previous ISSC report in 2012. However, since then only a few small-scale OTEC prototypes were installed in Japan and in Hawaii, US and there is no significant development of such technology. The committee decided not to discuss this type of offshore renewable energy in our report.

Mr. Stoev also mentioned the possibility to produce hydrogen from hydrogen sulfide (H2S) through a decomposition process and to use it as a source of renewable energy. This technology was not discussed in our report either. The study by Haklidir et al. (2006) indicated that there is a need for production of hydrogen from hydrogen sulphide in the Black Sea since it possess a great environmental threat and also there is a potential for storage of hydrogen in that area. However, the technology for the decomposition process should be further improved and the technology of offshore structures for accommodation of such process should also be developed.

2.2.3 Feargal Brennan

The comments on the current report and the suggestions for the next committee made by Prof. Feargal Brennan were highly appreciated. Prof. Brennan pointed out that if the committee report tries to cover all of the offshore renewable energy technologies which are as of today in very different development stages, the report might lose a clear focus on the most important technology (i.e. offshore wind) in this sector and the related challenges. The committee agrees with Prof. Brennan’s view on this. Moreover, due to the different maturity of the wind, wave and tidal energy technologies, the challenges and the priorities for research and development are different for these technologies. It is very likely that some of the technical challenges facing the offshore wind industry today, for example developing cost-effective installation methods, would be relevant for the wave energy industry in the future. However, the wave energy technology has not reached the level of commercialization in which mass-installation plays an important role for cost reduction. Most of the research on wave energy are related to the development of a concept for operational conditions with focus mainly on power production and partially on structural design. This makes it difficult to identify all of the common challenges for the three technologies.

Prof. Brennan also suggests focusing on structural matters in the next committee. We fully agree with him and it should be mentioned that this is in line with the mandate of our committee in ISSC. When preparing this report, we have tried to focus on structural issues for offshore renewable energy devices. There were not so many research activities on structural strength of such devices and the experiences from the offshore oil & gas industry seem to be well adopted in this regard. The main challenge is to determine the structural responses under simultaneous environmental loads from wind, waves and current. However, due to the strong coupling between the external loads and the induced structural responses, it was inevitable to discuss some of the details about the subjects that were beyond the scope of ISSC, for example wind turbine aerodynamics and automatic control.

We also thank Prof. Brennan for providing a list of the papers from his group that were not referred to in our report and the information about a few joint industry projects on offshore wind turbines that will be concluded during the period of 2015-2018, which the next committee can investigate in detail.

2.2.4 Kim Branner

Dr. Kim Branner has raised an important question about the increase of cost of energy (CoE) in the recent development of offshore wind farms and the solutions for cost reduction. He referred to Figure 4 in our report, which was extracted from the report issued by IEA (2013). Actually, CAPEX was referred to in Figure 4, not CoE which also includes OPEX. The main reason for increased capital cost in particular since 2010 is that the wind farms are installed farther from the shore and in deeper waters, which increases the foundation, grid connection and installation costs (IEA, 2013). Since the foundations of offshore wind turbines and their installation makes up an important part of the total cost, the focus of this industry is on one hand to optimize foundation designs, and on the other hand to reduce the uncertainties and therefore to increase the weather window for offshore installation. Novel foundation designs and cost-effective installation methods with pre-assembled turbines or using purpose-built installation vessels also have a potential for cost reduction. Moreover, the trend we observe recently is to deploy larger wind turbines (from 4-5 MW to 6-8 MW) and to increase the reliability of wind turbine components by better design in order to reduce the maintenance costs. These are the areas that deserve further research efforts.

Dr. Branner suggested adding reduction of the cost of energy to the mandate for the next committee. We agree with his suggestion.

2.2.5 Iraklis Lazakis

Dr. Iraklis Lazakis has kindly provided a list of the papers from his group with focus on operation and maintenance issues for offshore wind farms. These aspects were not discussed in our report and should be covered by the next committee since these are potential areas that can significantly contribute to the cost reduction of offshore wind farms in the near future. We appreciate these references from Dr. Lazakis.

Dr. Lazakis suggested the initiation of a benchmark study on the O&M tools developed for offshore wind farms. We think this is relevant and important for the improvement of offshore wind economics and we strongly recommend the next committee to put efforts on such benchmark study.

2.2.6 Tomoaki Utsunomiya

Prof. Tomoaki Utsunomiya commented on the cost of offshore wind turbines and in particular of floating concepts. We agree with Prof. Utsunomiya that the cost of energy (CoE) for floating wind turbines are very high at the moment because only a few prototypes have been in operation and there are no commercial farms of floating wind turbines yet. Moreover, we think the cost estimates are rather uncertain at this stage.

Prof. Utsunomiya also stated that there exists a big potential to reduce the CoE by mass production and cost-effective installation. He cited the report from Carbon Trust (2015) in which they concluded that the average CoE for floating wind turbines would be less than that of bottom-fixed wind turbines by the end of 2020s. However, it is the committee's view that when comparing the CoE of bottom-fixed and floating wind turbines, we should put them in a comparable manner. Site conditions such as water depth and distance to the shore will play an important role in such comparison. For bottom-fixed concepts, the cost of foundations would be roughly proportional to the water depth, while that of the floating foundations is more or less independent of water depth. In other words, there exists a water depth for which the cost of a floating wind turbine would be comparable to that of a bottom-fixed concept. Floating wind turbines are supposed to be deployed in deeper waters and relatively far from the shore. They will benefit from steadier and higher wind speeds (to produce more power) and probably also from easier installation with preassembled rotor and support structure (to reduce installation cost). On the other hand, there will be higher costs on grid connection and installation of mooring systems, in particular tendons in a TLP concept. These aspects are related to CAPEX. As for OPEX, it will be strongly dependent on the scenarios of maintenance, repair or replacement of wind turbine components. Floating wind turbines are much more difficult to access than bottom-fixed ones. However, floating wind turbines provide a possibility to disconnect the mooring systems and to be towed to the shipyard for major maintenance and replacement.

This might be more cost-effective than doing the work offshore, as it is the case for bottom-fixed wind turbines.

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