17th INTERNATIONAL SHIP AND
OFFSHORE STRUCTURES CONGRESS
16-21 AUGUST 2009
SEOUL, KOREA

VOLUME 2

SPECIALIST COMMITTEE V.4

OCEAN, WIND AND WAVE ENERGY UTILIZATION

COMMITTEE MANDATE

Concern for structural design of ocean energy utilization devices, such as offshore wind turbines, support structures and fixed or floating wave and tidal energy converters. Attention shall be given to the interaction between the load and the structural response and shall include due consideration of the stochastic nature of the waves, current and wind.

COMMITTEE MEMBERS

Chairman: F. G. Nielsen
K. Argyriadis
N. Fonseca
M. Le Boulluec
P. Liu
H. Suzuki
J. Sirkar
N. J. Tarp-Johansen
S. R. Turnock
J. Waegter
Z. Zong

KEYWORDS

Wind, Waves, Current, Energy, Converters, Loading, Design.

CONTENTS

1. INTRODUCTION

Since the completion of the report of this committee for the 16th ISSC (2006) significant developments have taken place within the field of ocean energy utilization. The development of fixed offshore wind turbines has matured to a point where it can now be considered a well-established commercial technology for shallow waters up to 25 meters. Several offshore wind farms have been put into operation and are operated like small power plants. This is supported by a large amount of publications on various technical aspects as well as the publication of an international standard and a number of design guidelines. Steel monopiles and concrete gravity foundations are by far the most often applied structures for shallow waters. For deeper waters, space frames are considered but not yet fully optimised. In even deeper waters, the development of floating wind turbines is at a stage where the first prototype is soon being erected. This is reflected in the literature by a diversity of publications on various case studies of different floating concepts.

Improvements in wave energy converter concepts have mostly resulted from at sea tests in dedicated trials of infrastructures and from a few industrial and commercial devices operating and connected to the electrical supply infrastructure. Aside from intermediate and full-scale tests, which benefited these concepts and devices, political and financial aspects played an important role: access to sea concession and feed-in tariff. The different avenues explored in the past decades (flexible and articulated bodies, oscillating water columns, water overtopping devices) remain relevant.

There has been a rapid rise in worldwide interest in the use of tidal currents for electricity generation. Although there are still only a limited number of actual installations, these have increased in rated power to a maximum of 1.2MW and are now connected to the electrical supply infrastructure. There has been a corresponding rise in the number and quality of published information concerning the assessment of resources and design of specific machines to match those resources. The reader is referred to the 2006 report for the discussion on the energy resources. The limited number of commercial scale devices means that there is still little published information with regard to the actual in-service response of structural aspects of tidal turbine design.

2. WIND

2.1 Overview of Current Wind Power Projects

In the last few years, a number of offshore wind farms have been put into operation in European countries such as Denmark, the United Kingdom (UK) and the Netherlands.

They are all situated in shallow waters, having a water depth of less than 25 meters and are relatively close to shore. For these developments, it proved economical to use either simple concrete gravity structures or steel monopiles as substructures (Musial and Butterfield, 2006).

A list of the offshore wind projects built in the last few years can be found at Wind Service Holland (2008). In terms of installed power, the main projects were the following: in the UK, the Lynn and Inner Dowsing (194 MW), the Kentish Flats project (90 MW) and the Burbo Banks project (90 MW); in the Netherlands, the Q7 project (120 MW); and in Denmark, the Nysted offshore Windfarm (165 MW) and the Horns Rev project (160 MW).

Projects are currently in development for deeper sites. The cost of the support structure and foundation will be a proportionally higher part of the total cost than for turbines in shallow waters. This means that finding an economically feasible design is vital for overall project viability. This necessitates the development of other substructure and foundation types than those previously used for shallow waters; an example can be found in Klose *et al*. (2007), where the development of a jacket substructure in 45 meters of water is described.

The most recent advance in wind farm development is the investigation of floating wind turbines in very deep waters. Significant efforts have been made to implement this modified turbine structure, especially in Norway (Skaare *et al*. 2006, 2007), the United States of America (Wayman *et al*. 2006, Jonkman *et al*.. 2007) and Japan (Suzuki and Sato, 2006)). A floating wind turbine prototype will be put into real sea test in Norway in 2009.

The design of support structures for offshore wind turbines (OWTs) has developed rapidly over the last decade. The following section pertains to the design of the substructure and foundation and how coupling it to the wind turbine and its supporting tower affects the design. Figures 1 and 2 show typical support structures.

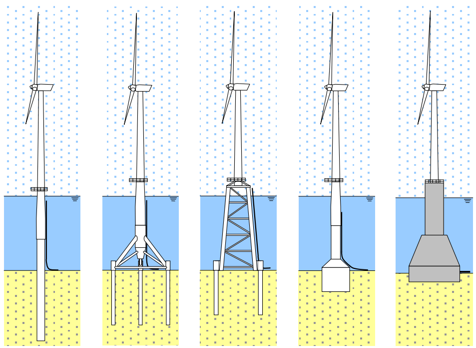


Figure 1: Typical fixed support structures (W.E. de Vries *et al*., 2007): monopile, tripod, jacket, suction bucket, gravity base).

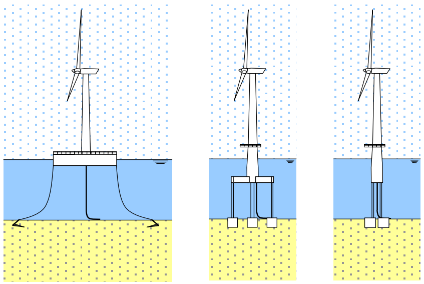


Figure 2: Typical floating structures (W.E. de Vries *et al*., 2007).

2.2 Integrated Design of Fixed Wind Turbine Structures

On the surface, it would seem that support structures for OWTs could be designed based on the design principles used in the oil and gas industry, and that OWTs would be very similar to their onshore counterparts. However, the industry has learned that this is only partially true; OWTs and their support structures require specific design requirements. The predominant design factors are reviewed in this section.

Contrary to offshore structures, where the dominant loading is typically from wave loads, offshore wind turbine support structures may be equally loaded by wind and wave loads. The load level is generally quite onerous, and the response of the entire system is dynamic. The dynamic nature of the response requires an analysis of the total OWT system, namely its tower and substructure. This analysis is referred to, hereafter, as an integrated analysis, as opposed to a separate analysis, which consists of the OWT and its tower as one piece and the substructure and foundation as another piece.

For the purposes of analysis, an OWT is characterized as a highly nonlinearly loaded elastic system supported by a substructure. The substructure may be approximately linearly loaded (fatigue loading) or nonlinearly loaded (ultimate loading) with an elastic or elasto-plastic response, depending on the load level. The analysis is further complicated by nonlinear foundation behaviour. For piled substructures, long-term soil behaviour, in conjunction with large pile diameters and the predominantly lateral loading, calls for special attention.

The effect of the soil properties on the overall stiffness estimation is significant. Small variations of soil properties may result in large variations of fundamental natural modes and, in some cases, resonance with rotor exciting frequencies. The estimates of stiffness for lower load levels are particularly expected to be imprecise because soil curves have traditionally concentrated on predicting load-bearing capacity rather than giving a detailed stiffness description. Lesny and Wiemann (2005) discusses this subject and concludes that stiffness is underestimated. However, the analysis is limited to 2-D soil models and certain Coulomb soil models which are thought to be debatable (Lesny and Wiemann, 2005). 3-D and other soil models lead to higher stiffness than current practice.

The combined lateral and axial loading of OWT foundations leaves room for optimization regarding pile lengths because ultimate tension capacity is underestimated. Still, many questions exist concerning cyclic tensile loads (Achmus *et al*. 2007).

Scour creation is another important issue to consider during design and analysis, especially considering the unfavourable condition of large-diameter structures in shallow waters. These aspects have been investigated in Nielsen and Hansen (2007) and Offshore Center Denmark (2006). It is worth noting that current experience regarding bearing capacity, cyclic behaviour and scour for piles is based on experiments using piles with diameters relevant for the oil and gas industry. The piles used in the offshore wind monopile foundations have a diameter larger than 4 meters and are also considerably stiffer. Another significant difference from the typical oil and gas design is that the pile's main exposure is lateral loading rather than axial (Lesny and Wiemann, 2005).

Considering the above nonlinear sources of loading and response, the de facto analysis tool is a time domain analysis that may reproduce the aforementioned nonlinearities. In general, experience shows that fatigue is the dominant design consideration for OWTs and their substructures.

A common design approach is simulation of turbulent wind fields and wave trains in the time domain. The dynamic response is calculated for each time step using the blade element theory for the wind loads and, typically, the Morison equation for the wave load. An example of the integrated analysis model used by Germanischer Lloyd (GL) for the fatigue analysis of the DOWNVInD research project (Klose *et al*. 2007) is shown in Figure 3. The analysis was carried out using the Bladed software, a 5 MW turbine with a rotor diameter of 126 meters and the model of the support structure as shown.

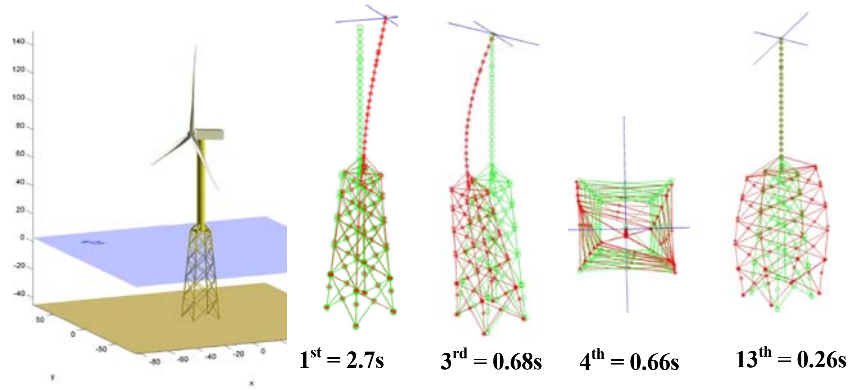


Figure 3: Support structure model for load analysis and typical eigenmodes of the jacket used in DOWNVInD, (Klose, 2007).

To produce fatigue load time histories, stochastic wind fields are generated for different wind speed bins (characterized by mean wind speed and turbulence intensity) and accompanying wave trains (characterized by significant wave height and peak period). Using the fatigue load time histories as load input, the response of the structure is calculated and the hot spot stresses are analyzed with the rainflow method and extrapolated with a Weibull distribution to cover the whole design lifetime.

The drawback of integrated analysis is that the procedure is time consuming; extensive calculations are needed since several seeds of 10-minute-long time histories have to be generated per bin to achieve statistically acceptable results. It should be noted that the use of 10-minute-long time histories is relevant for structures with eigenperiods around a couple of seconds, while floaters with significantly larger eigenperiods will require much longer time histories to capture both high and low frequency phenomena.

Most of the first-generation, shallow water OWT developments were designed using simpler methods, as the necessary computer software for integrated analysis has just recently become available. When using simplified analysis methods, the correct phasing of wind and wave loads and the mutual interaction of the loads (e.g., aerodynamic damping) due to the system's elasticity are difficult to accurately take into consideration. In an integrated time domain analysis, the calculation results in a correct phasing of wind speed and wave elevation, and the mutual interaction between the wind and the wave load is inherently taken into consideration.

The integrated analysis is still time-consuming, and simpler design methods are desirable. These simpler methods for the design of monopiles have been developed and used with some success as described in Kühn (2001); however, they have not been verified for a large turbine on a transparent and relatively stiff structure in deep water, such as that used for the Beatrice development. A more recent development is a frequency domain method for calculation of the fatigue damage of the substructure developed by Van der Tempel (2006). This method, as described in recent and not yet published work, has been found to yield results that are comparable to the outcome of time domain simulations for two test structures (monopiles). The frequency domain method may have potential to accurately model other structures as well, but since this has not yet been demonstrated, the use of the frequency domain method should be limited to preliminary design.

2.3 Floating Wind Turbine Structures

2.3.1 Design of Platform

A wide range of platform types are being investigated for the floating wind turbine structure. Platform types are semi-submersible; barge; spar-buoy and, tension leg platform (TLP) (Musial and Butterfield, 2006).

The first major design choice is the number of wind turbines to be installed on a platform; the choices consist of the one-floater-one-turbine concept or the one-floater-multiple-turbine concept. For the multiple-turbine concept, spacing between wind turbines must be large enough to avoid interaction between turbines, which inevitably makes the platform larger. Generally, a large-size platform improves motion characteristics, but strength becomes a central issue. Economic feasibility also influences the design choice. The multiple wind turbine concept was investigated in two research projects. In a project for the National Maritime Research Institute, Yago (2008) investigated a plane lattice-like platform, categorized as a barge. Initially, a three-wind turbine concept was pursued, but due to the strength issue, the number of wind turbines had to be reduced to two. Phuc and Ishihara (2007) investigated another type of multiple wind turbine support, the oval hub-spoke semi-submersible platform with three wind turbines, for the University of Tokyo and Tokyo Electric Power Co. joint research program.

Some of the most commonly researched platforms can be seen in Figure 4 below. Although not shown in Figure 4, the TLP is advantageous because the motion of the system is effectively constrained, and it can be economical if the foundation can be provided at a lower cost (Shim and Kim, 2008, Jensen and Mansour, 2006). The motion characteristics of a semi-submersible platform are good, but the turbines are still subjected to some amount of motion. The suppression of motion is one major research area for this type of floater. Construction and installation of the semi-submersible platform is easier in comparison to other types of floating platforms. The spar-buoy platform is built as a tall structure in order to make the centre of gravity lower and the buoyancy centre higher (Fukumoto *et al*. 2006). Suzuki and Sato (2006) investigated the effect of a fin to improve pitching-motion characteristics. The fin can reduce the rotational motion of the platform about the vertical axis due to uneven wind load on the turbine because the fin will add hydrodynamic mass. The fin is also effective in moving the natural periods of roll, pitch and yaw away from the wave period range by the added mass, and is also effective in reducing the motion of the platform by the augmented damping. The fin-equipped floater is also wave resistant and may be suitable for a harsh environment.

A demonstration unit of the StatoilHydro floating wind concept equipped with a 2.3MW Siemens turbine is scheduled to be installed offshore the west coast of Norway during 2009. This unit part of an extensive development programme and is planned to be on site for two years.

One futuristic platform concept is the sailing-type floating wind turbine, seen in Figure 4. In this study, Manabe (2008) looks at how feasible it is to utilize wind energy far from shore. The system cruises about the ocean, avoiding excessive storm conditions, and navigates from one area to another searching for good wind conditions. Hydrogen is produced from the generated wind power and transported to land.

Lattice type barge Spar with fin Semi-submersible Sailing type Oval hub-spoke type semi-submersible

Figure 4: Floating wind turbine concepts, Manabe(2008).

2.3.2 *Criteria for Design of Platform and Technological and Economical Feasibility*

In most research projects concerning floating wind turbines, it is assumed that land-based wind turbines are installed on a floater with minimum modification to reduce the overall cost. For this reason, strict limits are imposed on the motion of the wind turbine. For example, five degrees is allowable for a static inclination and one to two degrees is allowable for the amplitude of pitching motion considering inclination and acceleration effect (Yago 2008).

The relevant technology for floating platforms intended to support floating wind turbines is available from the offshore oil industry. The major challenge is to design an economically feasible floating wind turbine under the constraints imposed by the purpose of the structure.

For floating wind turbines, a larger platform is preferable to keep the motion to a minimum. However, the weight of the wind turbine to be installed on the floater is minimal, especially in comparison with the floater's buoyancy capabilities. For this reason, it is relatively easy to install a large wind turbine on a floater, and economies of scale hold true in this case for floating wind turbine technology.

2.3.3 *Analysis of Dynamic Response*

The effect of platform motion on the strength of the blade and shafting is a key issue in designing the wind turbine and platform. The effect of motion on the wind turbine has been investigated for the land- based wind turbine, but the floating wind turbine will be subjected to a greater range of motion. Skaare *et al*. (2006) and Suzuki and Sato (2006) developed an integrated analysis scheme of the whole system. The effect of greater motion, especially inertia force induced by the rotational, translational and angular combined motion of the blade, was formulated more precisely in their work. Skaare *et al*. (2007) also demonstrate the importance of including the blade pitch control system in the analysis. They also show that the control system used for fixed wind turbines must be modified when the turbine is mounted on a floating foundation.

2.4 Design Standards for Fixed Wind Turbine Structures

Recently, the International Electrotechnical Commission (IEC) completed the FDIS (Final Draft International Standard) for the IEC 61400-3 standard (2008) with principles and requirements for design of offshore wind turbines. The IEC standards have world-wide recognition as the technical basis for design and certification of wind turbines. All major wind turbine manufacturers, research institutions and certifying bodies participated in the development and maintenance of the IEC standards relevant for wind turbines.

Due to the significance of the wind loading, the large effect of control and safety system actions, and the sophisticated aeroelastic response of the rotor, the definition of design load cases for offshore wind turbines is much more complicated than that for offshore oil and gas installations.

For the common type of modern offshore wind turbines, ultimate wind-induced loads for design can occur at wind speeds in the operating regime. The control and safety systems protect the rotor speed of the turbine from overloading. If this level is exceeded, the safety system will bring the turbine to a stop and disconnect the electrical grid. Emergency stops will typically lead to large turbine loads, particularly when the stops occur at the same time as wind gusts. Modern offshore wind turbines pitch the blades during storm conditions to minimize the blade loads. In this mode, the largest tower bottom movements are typically crosswise relative to the wind direction. Some of the most advanced wind turbines even include tower vibration control by pitching the blades. Such advanced control systems reduce not only the wind-induced fatigue response, but also the wave-induced fatigue response (through the aerodynamic damping).

Aerodynamic damping is the main contributor to total damping in line with the wind (i.e., perpendicular to the rotor area), while the lateral aerodynamic damping in the cross-wind direction is much smaller. For the cross-wind direction, the important damping sources are those arriving from damping in the material and in the soil. Since these contributions are relatively small, especially at sites with dense sand soils (Liingaard 2006), active damping devices are often introduced in the structure itself to provide sufficient damping.

The main code for the design of wind turbines, the IEC 61400-1 (2005), defines loads using both stochastic wind input and transient deterministic wind input as well as defining worst case scenarios such as extreme wind gusts, extreme wind shear and extreme direction change. Load cases refer not only to normal operation, but also to fault conditions such as loss of grid and controller errors. Wind turbine response used as a basis for the design is computed as time simulation by aeroelastic software codes.

For the design of offshore wind turbines, the load cases from IEC 61400-1 (2005) must be modified to include relevant marine loads from waves, current and ice. Stochastic wind loads are combined with stochastic marine loads and deterministic transient events are combined with deterministic or stochastic marine loads. In principle, it is straightforward to combine wind turbine specific and offshore specific load cases, but as discussed in the following, the practical solution to the problem is far from obvious or simple.

Extreme wave loads typically govern the design of conventional fixed platforms, and the dynamics associated with the extreme wave load is often modest. Therefore, conventional offshore standards emphasize a correct derivation of the wave loading using nonlinear, higher order wave theories and focus on methods for quasi-static response analysis in combination with simple dynamic amplification procedures. In contrast to conventional offshore design standards IEC 61400-1 (2005) and other wind turbine standards explicitly require a full, nonlinear dynamic response calculation to be carried out due to the dynamic response behaviour of wind turbines. The logical extension of the load cases for extreme wind would include extreme wave conditions by simulating irregular nonlinear wave trains. However, methods for stochastic simulation of irregular nonlinear wave trains are still the subject of ongoing research and very time consuming. Hence, a compromise between the need for dynamic response calculations and an accurate account of wave kinematics must be found. Typically, one needs to make a quasi-static evaluation of response in order to properly account for nonlinear wave kinematics of extreme waves. It is also necessary to perform pseudo random response simulations in order to examine possible dynamic amplification of the wave loads.

The need to properly address both nonlinear wave loading and the dynamic response has been addressed in IEC 61400-3 (2008) so that this code contains a rigorous specification of design load cases that address all operating conditions in combination with applicable external loads. The users of the standard should – according to the opinion of this ISSC committee – be aware of some special issues related to the required analysis methods.

The combination of wind and wave storm events is still a partially unresolved matter. Conservatively, it should be assumed that the extreme wave and wind events occur during the same storm as adopted in IEC 61400-3 (2008) and Tarp-Johansen *et al.* (2006).

One attempt to overcome the separated stochastic and nonlinear regular wave analysis in the storm situation is through the introduction of the embedded wave concept. In this, a nonlinear regular wave, with the height and timing characteristics of the extreme wave, is artificially embedded within the wave time series. Further, this new wave train is combined conservatively with the 50-year, 10-minute wind event in such a way that the extreme wave occurs during this extreme wind event (10-minute time series).
Another issue, investigated during standard development, is the extrapolation of load effects. Due to the characteristics of the wind turbine operation, extreme load effects may occur even at low wind speeds as a function of control setting and other causes.

Significant effort has recently been put into the extrapolation of ultimate loads of wind turbines – onshore and offshore – from turbine loads obtained by simulation or measurement (Agarwal and Manuel, 2007a). For the Blyth site, the loads for a 2-MW wind turbine at a mean water depth of about 9 meters, 1 kilometre from shore was analyzed. It was shown that turbulent wind from land governed extreme loads and that wave heights had a lesser influence than wind, though some tower dynamics were induced by the waves (Agarwal and Manuel 2007b). Extrapolation of loads was not introduced within IEC 61400-3 (2008) since the joint consideration of all significant parameters (wind speed, significant wave height and period, as well as directionality) would result in an excessive amount of required analysis. Omitting some of these influences could lead to misleading results.

An additional issue to be considered is the misalignment of wind and waves. In Trumars *et al*. (2006) it was found that the influence of wind-wave misalignment shall be considered in foundation load analysis, while the influence of directional spreading of the waves was not clearly seen.

The present edition of the IEC 61400-3 (2008) has standard tables for 35 different load cases (operation, standstill, transients, fault conditions, etc.) resulting in the order of 1000 simulations of 10-minute time series. The introduction of directionality and misalignment results in a very large number of simulations. This motivates a screening process, during preliminary design, to determine the most important load cases for the design in question. Further, lumping of the sea states is often acceptable to reduce the number of FLS simulations (Kühn 2001).

Experience from built projects has shown that the design driving ULS load cases are those associated with the storm cases. These load cases have important implications for the required pile penetration depth for the monopile. In some applications in which wind loads dominate the design, extreme operating gusts (gusts of extreme amplitude at lower wind speeds) or safety system driven stop procedures tend to be decisive for the support structure. For structures in ice-infested areas, ice loading is expected to be the main strength design driver (Tuomo Kärnä, 2006).

In general, the fatigue loads govern most parts of the support structure design. For these loads, the effects of wind-wave directional distribution and misalignment, damping and associated dynamic amplification, as previously discussed, play the dominant role.

IEC 61400-3 (2008) does not include specific component design requirements or design formulas. The standard relies on the use of recognized design standards as the basis for the sizing of the structural elements in the support structure. It generally makes reference to the ISO standards as shown in Figure 5. IEC 61400-3 (2008) also allows for the use of other industry guidelines, such as GL, DNV and API. It is required that, when partial safety factors from national or international design codes are used together with partial safety factors from IEC 61400-3 (2008), the resulting safety level shall not be less than the intended safety level inherent in IEC 61400-1 (2005).

While the U.S. has a long history of onshore wind power development, offshore wind power resources remain largely untapped (Saigal *et al*. 2007). Only a few offshore wind farms have been proposed for U.S. waters, but none have yet been constructed. A few years ago there was a major change regarding the permitting of OWTs in the U.S., as well as how design standards are likely to be applied. Prior to 2006, the U.S. Army Corps of Engineers was, according to Tarp-Johansen *et al*. (2006), the lead agency in permitting offshore wind energy facilities. With the Energy Policy Act of 2005, the jurisdiction was transferred to the U.S. Department of Interior's Minerals Management Service (MMS). The MMS has been the agency responsible for permitting the offshore structure of the oil and gas industry, and it is expected that they will apply their experience in that area to the topic of offshore wind. Generally, the MMS philosophy is to require that the reliability of new types of offshore facilities be equal to or exceed the reliability levels of currently accepted facilities. However, the results from Tarp-Johansen *et al*. (2006) indicate that one should exercise caution in applying these standards to OWTs without a thorough investigation of the economic consequences.

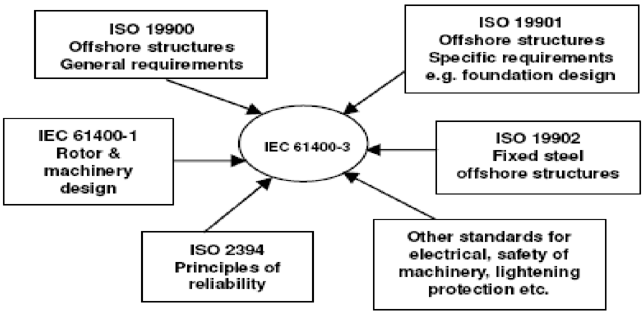


Figure 5: Reference to other standards in IEC 61400-3 (2008), Saigal *et al*. (2007).

While the U.S. Army Corps of Engineers was the lead agency regarding offshore wind in the U.S., the issue of which design standards to use was not widely discussed. Most observers were led to conclude, by default, that the standards being developed in Europe would probably be utilized in the U.S. as well. But effectively there are no current guidelines that have been accepted by the MMS or other U.S. agencies for the design of offshore wind power generators and their support structures in U.S. waters.

The MMS has significant experience with the design, fabrication and installation of traditional offshore structures and utilizes the American Petroleum Institute's (API) Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms (API RP-2A WSD, WSD stands for Working Stress Design) as the basis for regulating offshore structures in U.S. waters. Seen in that perspective, it makes sense to utilize the huge amount of experience built into the API standards when designing support structures for OWTs. However, as API RP-2A does not address the special conditions that are required for the design of wind turbine support structures, it is also envisaged that API RP-2A would have to be adapted or supplemented with other standards if it were to be used as the basis for wind turbine support structure design.

In order to obtain an indication of the inherent safety level in API RP-2A, as compared to the safety level required in IEC 61400-1/IEC 61400-3 (2005/2008), some initial comparisons have been made. In Saigal (2007), comparisons of wind loading alone across the two standards and wave loading alone across the two standards have been made. However, no comparisons of combined wind and wave loading have been possible as the different scope for the two standards does not make such comparisons realistic. The indication was that API RP-2A is the more conservative of the two standards, but it should be noted that these results are preliminary and do not reflect a complete comparison of them.

In this context it should be noted that the objective for IEC 61400-3 (2008) has been that OWTs should have the same level of structural reliability as current onshore wind turbines as specified in IEC 61400-1 (2005).

It appears that the design of OWTs is governed by a mix of fatigue loads, various operational extreme loads and extreme loads during extreme environmental conditions to a much larger degree than would be the case for offshore structures used by the oil and gas industry. Indeed, some of the important loads for OWTs are not addressed in offshore design practice, and the recommended methods for determining the structural response are different. The conclusion is that applying the API or the ISO 19902 standards to design OWTs is not feasible, to a large extent because wind turbine design practice and the design practice for typical bottom-fixed offshore structures varies due to the difference in the physical behaviour of the two types of structures. Contrary to this finding, it is feasible to reference the mentioned codes for the resistance calculation as an integrated part of IEC 61400-3 (2008) design procedure.

3. WAVES

3.1 General

3.1.1 Systems in Operation or Under Development

Some wave energy converters have been raised to an industrial level and installed at sea, connected to the grid, and produce electrical energy. Several Pelamis devices (Retzler 2006) are now in operation off the coast of Portugal, with three units of 750 kW each, the last installed in September 2008. The rise of the Pelamis from a wave basin model scale to a full-scale device is probably related to the use of extensive at-sea tests of a prototype, in this case at the EMEC in Orkney Islands. An important factor for the development and installation of such converters is the feed-in tariff.

An at-sea measurement of the overtopping flow was made onboard the 1:4.5 scale Wave Dragon overtopping device (Tedd and Kofoed, 2009). The system has been undergoing testing since 2003 in the Danish inlet which has wave conditions resembling the downscaled North Sea climate (Kofoed *et al*. 2006, Tedd and Kofoed, 2009). The prototype was fully equipped with turbines, control systems and instrumentation to measure power production, wave climate, motions of the floater, mooring forces and structural stresses. These data are compared to theoretical modelling and allow for the discussion of the independency of the running waves and body response.

Boström *et al*. (2008) tested an offshore Wave Energy Converter at the Swedish west coast. The device is based on a directly driven permanent linear generator located on the ocean floor and driven by a point absorber. The research was focused on the conversion of wave to electrical power by the direct drive system.

Places where full-scale or intermediately sized wave energy converters can be tested in real conditions at sea have been specially developed during the past years. They consist of sea areas exposed to waves and other metocean processes, fitted with an electrical connection to the grid, various environmental sensors and other logistics such as sea bottom mooring and supply vessels. These full- scale experimental facilities allow for a better understanding of the wave energy device's response and energy conversion and production. However, they do not represent industrial wave farms as they do wind farms described in Chapter 2. Among the dedicated places are EMEC in Scotland; the "Wave Hub" off the north western coast of Cornwall in the UK; the SEM-REV under development in South Brittany in France, (Mouslim 2008) and the Portuguese Pilot Zone in the west coast of Portugal (Huerta-Olivares *et al*. 2007).

Numerical studies and model scale tests of the SEAREV concept, as well as its electromechanical basics, have been accomplished and it now needs full- or intermediate-scale tests at sea, Babarit *et al*. (2006), Kerbiriou *et al*. (2007).

Figure 6: Three P1-A Pelamis machines with capacity of 2.25MW, 5 km off the west coast of Portugal (substation of Aguçadoura).

3.1.2 *Practical Limits*

Falnes (2007) presents a review of wave energy extraction, starting with a discussion of wave spectrum parameters that are related to the transport, distribution and variability of the wave energy. An equation is derived for fully developed seas, which shows that the power flow intensity is up to five times larger for ocean waves than for the wind that generates the waves. It is known that wave energy is more spatially concentrated and persistent than wind and solar energy; however, there are limits to the amount of energy that can be extracted from the waves. Considering optimum wave interference, Falnes (2007) presents an upper bound to the amount of energy that can be extracted by an oscillating system (line PA in the graph of Figure 7). Optimum wave interference, for a single oscillating system, occurs at the resonance frequency and for specific amplitude of the motions of the oscillator. Resonance means that the excitation force and the velocity of the device are in phase.

Due to the limited size of the device, the power that can be extracted for longer wave periods is much smaller than the former bound. Budal and Falnes (1980) derived another upper bound that takes into account the limited volume of the immersed oscillating system (line PB in Figure 7). In order to extract the maximum energy (i.e., to approach as much as possible to the theoretical bounds), it is necessary that the shape of the immersed volume is well designed and the control strategies are used to keep the phase between excitation and velocity close to zero for different wave periods.

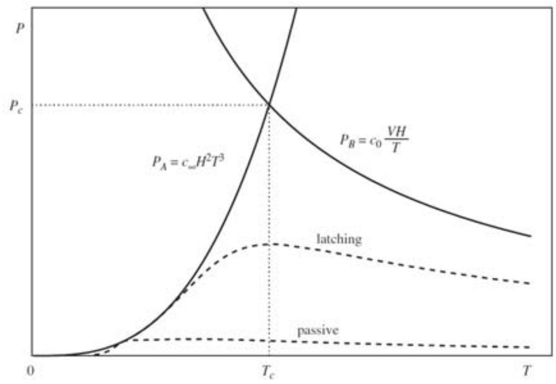


Figure 7. Two upper bounds for the power that can be extracted from a sinusoidal wave of height H and period T by means of an immersed body of volume V (Falnes 2007). The two dashed curves represent the power absorbed by a semi-submerged finite-volume sphere heaving with optimum amplitude (optimum load obtained by latching) or without phase control (passive).

3.1.3 New Developments

Since the first ISSC (2006) report on ocean energy utilization, no obvious breakthrough has been observed in the domain of the wave energy conversion principles. Major improvements are related to the conversion technologies. Leijon *et al*. (2006) and Agamloh *et al*. (2008) illustrate ongoing studies on electric converters directly driven by floaters experiencing oscillatory motions in waves. In the first case the resulting heave motion is linearly transmitted to the electrical converter; in the second case the translation motion is converted to a rotational motion through a ball screw. In the Archimedes Wave Swing concept, Valério *et al*. (2007) describes linear electrical converters driven by the motion of underwater floaters and submitted to various control strategies: phase and amplitude control, reactive control, latching and feedback linearization, in order of increasing efficiency.

Works on air-flow turbines dedicated to Oscillating Water Columns are still underway to improve their efficiency, Torresi *et al*. (2008), Thakker and Abdulhadi (2008), both with Computational Fluid Dynamics and experimental methods. In the category of moving body converters, latching control remains a promising tool, Babarit and Clément (2006), Falnes (2007).

The use of submerged horizontal plates to extract energy from the waves was proposed several years ago by Graw (1993). The principle is based on the fact that an oscillatory horizontal flow is generated below the plate as the wave passes through the plate. The energy can be extracted with a water turbine. The concept was re-examined by Orer and Ozdamar (2007) who carried out experiments and concluded that by locating a vertical wall below the plate, the ratio between wave power and the power of the flow below the plate can be up to 0.60. The wave power is calculated for the width of the opening area under the plate, while the water flow power is proportional to the opening area under the plate and flow velocity to the power of 3. Although the concept is interesting, the difficulties of installing a vertical wall at full scale combined with the very large wave forces expected to be generated on this wall make the implementation of the concept for real applications difficult.

Another concept, which saw a strong development over recent years is the near-shore bottom hinged flap device (Whittaker *et al*. 2007). It consists of a buoyant flap, hinged at the base, which is fixed to the sea bottom and located at shallow water depths. As the flap oscillates due to wave action, hydraulic cylinders are actuated to compress a fluid, which is transported under pressure to shore. The conversion to electricity takes place at the power plant onshore. One of the advantages of this concept is the large power-to-weight ratio and the fact that the production of electricity is done onshore. In extreme seas the flap can be lowered to the sea bottom. One of the disadvantages is the maintenance of the fully submerged system. Minor maintenance actions need to be done remotely or by divers. For major maintenance, the device includes a ballast/de-ballast system, which enables installation and removal with the aid of a small service vessel. An alternative top-hinged, flap-type wave energy converter was studied by Folley *et al*. (2007).

The ANACONDA concept was recently proposed (Chaplin *et al*. 2007) see Figure 8. This is a large water-filled rubber tube, aligned in the direction of wave propagation, in which the natural propagation speed of bulge waves is matched to the speed of the water waves to be captured. The bulge wave power is converted to electricity by a turbine, which receives a flow smoothed by accumulators. Model tests have shown that the capture width is up to four times the diameter of the tube.

Figure 8. Artist view of the ANACONDA concept. Photo Credit EPSRC.

3.2 Environmental Conditions and Loadings

Implementation into a real environment requires a better analysis and description of the waves field and its influence on the power take-off as described by Kerbiriou *et al*.(2007). In particular, the decomposition of the sea states shows several indicators such as different swells and wind waves, and gives a more reliable description of the resource, loads and energy production. In addition, new types of useful measurements can be delivered by satellites, Mackay *et al*. (2008), extending the knowledge of the wave's resource from several located points to geographical areas.

A review of wave energy resources and extraction and associated mathematical tools can be found in Falnes (2007). Cruz (2008) edited an extended collaborative work on the analysis of past and present knowledge and technology in this field, including impact assessment and opening on future developments.

Full-scale measurements of the wind, current (Muller *et al*. 2007) and waves field can be assessed by the use of High-Frequency Radar, Saillard *et al*. (2005). In particular, the wave field can be described by an area demonstrating tenths of square miles in a scale representation of a wave energy farm, Cochin *et al*. (2006). Acoustic Doppler Current Profilers (ADCP) are often used to measure slowly varying current profiles at sea or in coastal or offshore environments. The use of ADCP at a rather high frequency still needs some improvement in data processing, to evaluate the waves and current interaction, Guinot *et al*. (2008).

3.3 Structural Response

3.3.1 Simulation methods

3.3.1.1 Overtopping

Overtopping WECs are based on the principle of overtopping and storing wave energy in a reservoir, which is then used to actuate a water turbine. The most efficient concepts use several reservoirs, placed one over the other, in order to extract energy from waves of different amplitudes. Vicinanza and Frigaard (2008) carried out an experimental program with a scaled model of an onshore overtopping device to characterize the wave structure interaction phenomenon and to measure the spatial and temporal pressure distributions. 2-D and 3-D sea states and severe sea states were used for the experiments. The authors conclude that the Weibull distribution, with appropriate parameters, is suitable to represent the probable distribution function of the pressures. The data are compared with the design criteria suggested by the Coastal Engineering Manual (CEM) for predicting pressure distributions on sloping structures and the authors observe that the criteria underestimate the measured data by 20 to 50 percent.

3.3.1.2 Moving Floaters

Griet De Backer *et al*. (2008) investigated the vertical slamming on point absorbers, including the control of the motion to reduce the slamming probability and the consequences on the power absorption. A review was made of analytical methods to calculate the slamming pressures on 3-D bodies and some results are presented for cones and hemispheres. Drop tests were carried out for the same shapes to measure the impact pressures. Although, the numerical results are about two times larger than the measured data.

Fonseca *et al*. (2008) calculated the expected maximum pressure distributions on the hull of the FLOW wave energy converter. The concept, under development by Martifer Energia, is a floating WEC, composed of two bodies connected by one degree of freedom articulation and the energy is extracted at the articulation point by a power take-off system. The numerical model, based on a boundary integral method, was calibrated using experimental data from model tests. Finally, the pressure distributions on the hull are calculated in the time domain for selected storms, while the probability distributions are obtained from frequency domain-determined variances.

3.3.1.3 Oscillating Water Column

Analysis of the Oscillating Water Column (OWC) devices focuses on the turbine efficiency and overall efficiency of the system in terms of power take-off as described by Perdigão and Sarmento (2003). The water motion is linearly modeled, the airflow is considered as isentropic and the turbine control of the flow is emphasized. Josset and Clément (2007) gives a detailed description of the various functions involved in the potential flow modeling of a generic OWC device. The outer and inner water flows problem are coupled and lead to the hydrodynamic coefficients in time domain and resulting loads on the structure after solving for the isentropic airflow. Application to the practical case of the Pico plant makes it possible to evaluate and improve the Power Take-Off by tuning the turbine efficiency. The risks associated to the inner free surface motion are also discussed. The model can be used for monitoring the device.

3.3.2 Mooring Analysis

Floating wave energy devices are dependent on adapted and reliable mooring. Two key situations are likely to occur. First, the mooring may be part of the energy conversion process. In this case, floating buoys may be connected to underwater energy converters such as directly driven electrical converters or hydraulic engines. In this scenario, single or multiple taut mooring lines can be working and a secondary mooring system may be involved. Second, the mooring is only dedicated to maintain the floating body in a position compatible with its operation. The mooring can consist of single or multiple lines of various shapes (catenary lines, tendons, composite with intermediate buoyancies or weights) and materials (chains, cables, fibre ropes). In both cases, the mooring system must ensure various purposes:

- Maintain the device with acceptable excursions around a mean position.
- Comply with acceptable tensions induced by the tide level, current, wind and waves.
- Limit the loads in the other components such as the electrical connectors, umbilical driving fluid and the device itself.
- Ensure sufficiently long service.

In addition, the mooring system must fulfil some technological requirements such as easy installation, maintenance and decommissioning for single or multiple devices.

Solutions arising from the oil and gas industry or from coastal engineering are applied, but must cope with the large amplitude motions imposed on wave energy converters and resulting loads, though this aspect is sought to be minimized under other circumstances.

Some experiments in laboratories, or at sea and nonlinear numerical modelling, have shown the importance of the mooring design on the line tensions and device motions, Kofoed *et al*. (2006) and Johanning *et al*. (2007).

The response of the system has to be considered from several points of view. Theoretical modelling of WEC in the available literature is primarily made through a linear approach in the frequency domain and sometimes several second-order refinements. In the linear case, the mooring system is taken into account as a linear system with a linear stiffness matrix, but must also allow for additional mass and damping matrices, resulting in a global impedance matrix which can be issued from time-domain simulation (Fitzgerald and Bergdahl, 2008), or from analytical considerations.

Second-order forces can be quite easily computed with now nearly standard computer codes giving the Quadratic Transfer Functions (QTF). The low-frequency QTF are particularly involved in the drift motions of moored bodies inducing low-frequency excursions related, most of the time, to the horizontal resonant motions. Both mean and oscillating forces are then induced into the mooring lines.

Time-domain simulation is often used to evaluate the low-frequency response of the system. This method is time consuming and needs many simulations to allow any statistical or probabilistic approach, especially for the determination of extremes. For that purpose, works initiated in the offshore industry domain for the analysis of low-frequency motions of FPSO are promising. The time simulation can be performed more quickly by a proper handling of the QTF, and the second-order statistics can benefit from some direct methods (Prevosto *et al*., 2007).

Fitzgerald and Bergdahl (2007) compared different alternatives for the design of the mooring cables of a cylindrical floater, similar to a point absorber, in 50-meter water depth. The lines are designed according to the ultimate limit state criteria of Det Norske Veritas (DNV-OS-E301) and the environmental conditions include design wind speed, current, steady drift force and wave frequency motion (slowly varying forces are not considered). The authors consider different line configurations and materials and compare the designs in terms of several criteria. It is concluded that simple catenary moorings are not very efficient. Submerged or surface buoys may have a beneficial effect, and the use of synthetic cables with higher elasticity has the potential to reduce very much the overall weight of the system.

Johanning and Smith (2007) present the results from a large-scale mooring investigation at the Scapa Flow in Scotland: three slack mooring line configurations and a taut nylon rope line configuration were considered. The experimental data are compared to numerical results and the overall results discussed in terms of station-keeping criteria. It is concluded that the agreement between experimental data and numerical results is good. Slack moorings show a large increase in the tension when the line is lifted from the sea bottom, while the taut mooring with synthetic lines might have advantages in terms of load-excursion characteristics. More research is needed to understand the long-term behaviour of synthetic ropes under cycling loading due to environmental loads.

Johanning *et al*. (2007) discuss the static and dynamic mooring line damping and their importance for floating WEC machines. Experiments were carried out with a mooring line under horizontal motion in a wave basin to investigate the axial stretching and the upper-top end dynamics. Both free decaying tests and forced motion tests were conducted. It is concluded that the line motion has important dynamic effects when it becomes semi-taut. Dynamic effects are also important for high-frequency motions at the top end of the line. Damping due to the cross-flow drag also plays an important role in these cases.

Most of the theoretical/numerical work on the performance of WECs and their optimization to extract the maximum energy from the waves does not consider the influence of the mooring system. There are two reasons for this. First, it seems that for many WECs, the ratio between the installation depth and the dimensions of the floater is minimal; therefore, the mooring is of shallow water type. In this case, the dynamic effects of the mooring system are probably small. Second, if the dynamics of the mooring system are to be considered as a solution to the wave-floater interaction, then the problem becomes much more complex. The elastic and damping forces of the mooring system are highly nonlinear; in principle they must be calculated by finite element or finite difference methods, and the accurate coupled solution of floater plus mooring system must be obtained in the time domain. The mooring system may add a few hundred degrees of freedom to the dynamic problem. One possible approximate solution is to make linear the effects of the mooring lines and solve the linear problem in the frequency domain. Fitzgerald and Bergdahl (2008) implemented a solution based on this principle and discuss the results for a generic WEC with a cylindrical shape.

The correct characterization of the slowly varying drift forces is important for the design of the mooring system and, during operational conditions in which the contribution for fatigue damage is greatest; it is known that there is a relationship between the power extracted from the waves and the horizontal drift forces. Retzler (2006) presented the results of an experimental investigation of the slow drift motions, on the Pelamis WEC, induced by second-order wave drift forces. The most interesting conclusion is that the drift forces are mostly due to wave power absorption, with only a small contribution from the other components. The author concludes that because of the absorbed wave power, the Pelamis is subjected to considerably larger drift forces than a vessel of similar dimensions.

Fonseca *et al*. (2008) presented an analysis of the wave drift forces on an articulated floating WEC with emphasis on the effects of the wave energy extraction on the time history of the horizontal drift forces. The hydrodynamic calculations were carried out by a boundary integral method to obtain the motions and mean drift forces. The Newman approximation is used to obtain the complete low frequency QTF, which is then used to derive the drift spectrum and the time histories of drift forces for typical operational conditions. It is concluded that the extraction of energy significantly increases the horizontal drift forces.

One of the components of the mooring system is the anchor and, again, the experience accumulated by the offshore industry to moor floating systems can be used for WECs. However, specific aspects of these new structures should be taken into account: the characteristics of the lifetime dynamic loads, which are associated with the dynamics of the wave energy extraction; the probability of sliding of the anchor should be very small because the WECs are to be installed in wave farms, therefore, in close proximity between each other; and, different economics compared to offshore, etc. Ming and Aggidis (2008) discuss the different possibilities in terms of anchoring the floating WECs.

Measured data at sea provide important information about the statistics of the environment and the structure dynamics. Realistic results on return periods and extremes can be provided by the Response- Based Design approach for whatever variables are considered: wind, current, wave, and load motions. A limited number of variables (two or three) permit some analytical development, and methods such as the Inverse First Order Reliability Method allow the evaluation of joint probabilities (Nerzic *et al*. 2007, François *et al*. 2007).

3.3.3 Coupled Analysis

A coupled analysis is always necessary to determine the horizontal motions of floating WECs induced by slow drift wave exciting forces. In this case, the mooring line forces are coupled to the hydrodynamic responses of the floater. Due to shallow water mooring characteristics, hydrodynamic effects on the mooring lines (damping and inertial) can often be neglected. However, the elastic forces of the mooring system are highly nonlinear, especially for large horizontal displacements, meaning that the problem of determining design loads at the mooring lines and extreme horizontal motions of the floater must be solved in the time domain.

However, “coupled analysis” is usually used in a different context. Coupled analysis is necessary when the mooring dynamics and floater dynamics are coupled at the wave frequency. The mooring lines respond dynamically to the wave frequency motions of the floating structure imposed on them. Due to inertial and drag effects on the lines, they do not achieve their catenary shape instantaneously when excited by the motions of the fairlead; therefore, the behavior is dynamic in nature. The dynamic effects influence the maximum loads on the lines and they also affect the dynamics of the floater. The importance of the dynamic coupling increases with the water depth. Inertial and drag effects can be neglected for shallow water moorings.

Regarding the elastic effects of the moorings, in most cases of offshore floating structures, the system is designed to achieve a natural period of the horizontal motions that are much larger than the typical wave periods (approximately one order or magnitude larger). This means that the mooring system is compliant with the wave frequency exciting forces; therefore, these forces are mostly opposed by inertial effects instead of being opposed by the mooring lines. This design principle also seems to be the most common for WECs; however, there have been some proposals that suggest using the elastic properties of the mooring system to tune wave frequency motions of the floater, which optimizes the wave energy extraction. The disadvantage is that non-compliant systems will result in very large extreme loads on the moorings.

3.3.4 Control System and Response Mitigation

Many WECs will have active systems to amplify the motion response, thus optimizing the energy extraction. It is possible to use the active system to de-tune the motion responses in order to reduce response loads in survival conditions. As an example, the Pelamis can use its digitally controlled hydraulic system to de-tune the response in case of encountering adverse wave groups.

3.4 Stochastic Response

3.4.1 Stochastic Nature of Waves

The existing sea spectra have been derived for deep water. However, the waves modify their characteristics as they approach shallow water (presently offshore WECs are planned to be installed in water depths of around 50m). The existing wave statistics in the form of joint probability distributions of significant wave height and mean wave period (scatter diagrams) are also for deep water.

The important issue regarding the stochastic nature of the waves is probably the local effects due to bottom inclination, coast line effects and shallow water effects. This means that the characteristics of the waves are site specific. Ideally, they should be obtained from local measurements or calculated using wave propagation models.

Nonlinear effects in random waves are the main challenge. Second-order approximation remains a valuable tool to approach the low frequency loads and response of moored systems. Infra-gravity waves, which can be explained as the result of low-frequency, second-order waves reaching shallow water, constitute a particular field of investigation.

3.4.2 Extreme Event Analysis

To design wave energy converters, one needs to calculate the expected maximum loads that the system will encounter during its operational life. It is important to properly represent the hydrodynamic behaviour of the system and the stochastic nature of the sea states. Environmental loads that need to be considered for the analysis of the mooring system are mainly due to waves, current, and wind. However, for most devices and site locations, the wave loads dominate.

Since these systems are new and different from conventional offshore structures, semi-empirical formulas and procedures developed over the years and, based on the accumulated experience, in principle cannot be used. The calculation of the expected maximum loads on the structures should be performed with numerical models based on first principles. The stochastic nature of the combined action of waves wind and current loadings should be considered. The wave loads will normally dominate the response and should thus be treated in more detail than wind and current loads.

Direct calculations of the wave loads can be done by computer codes based on potential flow boundary element methods. However, the specific relevant characteristics of the WEC must be included in the code, as for example, articulations, multi-body dynamics, or multi-body hydrodynamics, effects of the power take-off mechanism (which may be used to reduce the responses), mooring system couplings, etc. It is expected that in most cases the extreme loads are affected by strong nonlinear effects, which means that ideally the direct calculations should be done by nonlinear codes in the time domain. The stochastic response analysis should thus be performed in selected seastates representative of the future area of operation.

There are several stochastic methods currently used, or proposed, for ships and offshore structures to estimate the maximum expected structural nonlinear loads. They are based on proper selection of the wave conditions to carry out the nonlinear simulations. Either the wave sequence is previously determined, by a stochastic process, as the expected most severe event or otherwise extreme value probability distributions are fitted to the simulated response. The reader is referred to the ISSC reports of the Loads Committee.

Expected maximum structural loads on the system during the structure's operational lifetime must be determined in order to design the structure. Since the loads are stochastic in nature, an appropriate procedure needs to be used to carry out the extreme event analysis. Because the systems are new and different from other offshore structures, the procedures for extreme event analysis should be based on hydrodynamic models, derived from first principles, together with proper stochastic characterization of the environmental loadings. Ideally and especially for new concepts, direct calculation should be combined with experimental data from model tests.

The developers very often do not have specific nonlinear codes to calculate the wave-body interactions for their systems. A possibility then is to apply standard linear frequency domain panel methods. Past experience shows that in many cases, the linear predictions overestimate the system responses; therefore, one can say the linear methods are conservative. This hypothesis must be analysed with care case by case. If linear hydrodynamic tools are applied, the prediction of maximum expected loads is easy and simply given by summation of short term Rayleigh distributions weighted by the probability of occurrence of the sea states. Ideally, for new concepts, the calculations should be combined with survivability model tests in a wave basin. Regarding wind and currents, constant values of the maximum sustained speeds can in principle be used for design purposes. The return period applied should be according to the standard applied for design.

Dealing with mooring and the low-frequency motions of floating bodies, Prevosto *et al.* (2007) compared several methods to evaluate the crossing rate level of a horizontal motion. The results reveal large deviations from the simulation-based assessment, taken as the reference solution, of the Rice formula with a Gaussian assumption. Three other methods – an asymptotic expansion approach and a Monte-Carlo integration approach, both developed by Hagberg (2004), and a projection method – appeared close to the reference solution. In particular, Hagberg's Monte-Carlo integration gives good approximations for high response levels.

Nerzic *et al.* (2007) studied the joint distribution of a couple of variables selected among waves, wind and currents parameters in an offshore situation. The Inverse First-order Reliability Method (I-FORM) allows for the calculation of the extreme environmental contours for a given return period. This method is of general interest and can be used to evaluate the design loads of WECs for given metocean statistics.

François *et al*. (2007) used the same I-FORM methodology to derive the extreme tension in mooring lines of offshore platforms. Up to three variables were taken into account.

3.4.3 Fatigue Analysis

Regarding fatigue analysis of WEC machines, linear frequency domain analysis may be sufficient to establish the fatigue damage in moderate wave heights. However, the validity of the linearity assumption must be examined in each case. Due to the intentional amplification of motions, latching, multi-body dynamics, etc., the wave-induced loads, even in small and moderate seas, may be nonlinear. If this is the case, nonlinear time domain approach, as for the extreme loads, should be employed. For bottom-fixed or taut-moored structures, load variations due to tide should be taken into account.

3.4.4 Structural Reliability

The mechanical behavior of WECs as any fixed offshore platform is affected by many uncertainties. Rational treatment of the uncertainties in design is ensured by the use of structural reliability analysis. However, depending upon if extreme loads or fatigue failure is considered, the major uncertainties to be taken into account may differ (DNV, 1995). However, the description of the random properties requires qualification in statistical analysis, regression methods, and random process identification (Ang and Tang, 2007).

In extreme conditions, the uncertainties come from the environmental loading, the wave-loading models, and the material ultimate strength. The environmental loading is described by the joint probability of waves, currents, and winds from available measurements or hindcast models (Nerzic *et al*. 2007). In estimating the wave-induced loading, the uncertainties come from the structural stiffness, damping properties, and mathematical idealization of the structure

3.5 Learning from Experience

One of the problems with the structural design of WEC devices is the fact that very limited experience with real operation is available. For this reason, it is advantageous to make information from full-scale testing in the sea available to be shared between the developers; however, no significant information has been found in recent literature. An undergoing FP7 European project named EQUIMAR, “Equitable testing and evaluation of marine energy extraction devices in terms of performance, cost and environmental impact,” has the primary aim to deliver a set of protocols for the equitable evaluation of marine energy converters. This will particularly profit from former model scale and full-scale experience.

3.6 Guidelines and Standards

In 2005, DNV issued "Guidelines for design and operation of wave energy converters," a work commissioned by the Carbon Trust as part of the Marine Energy Challenge (Carbon Trust, 2005). Since this industry is relatively new and involves several specific characteristics, it was not clear if (or which) existing codes and standards are applicable for the design and operation of wave energy converters. The objective of these guidelines is to provide interpretation and guidance on the application of various proven standards and recommended practices for the development of wave energy projects (as well as tidal energy devices). The guidelines give a basis to introduce the aspects of integrating reliability, feasibility, and risk management into the design and operation of these systems.

The document covers many topics related to the former aspects, but in particular it includes chapters on Structural Design Criteria, Foundation Design and Mooring Analysis, and Appendixes on Fatigue Analysis Methodology and Wave Modelling and Loads.

More recently, DNV issued an Offshore Service Specification for Certification of Tidal and Wave Energy Converters (DNV-OSS-312, DNV 2008). This document defines the requirements, philosophy, deliverables and the certification procedure itself. Together, the qualification process (DNV RP-A203 "Qualification Procedures for New Technology") and the "Guidelines for Design and Operation of Wave Energy Converters" define the framework for the certification activities.

Bittencourt (2007) describes the experience, related to the involvement of DNV, in the Qualification process of several projects for marine energy converters, and the use of the Guidelines for Design and Operation of Wave Energy Converters. The objective of the process is to obtain a good balance between the constraints, handling of uncertainties, financial targets, and functional requirements.

3.7 Needs In Terms of Research

A major challenge is related to the modelling of resonant systems with strongly nonlinear behaviour.

For conventional floating bodies, the purpose is generally to minimize the response for a given sea state. In the case of the wave energy converters, maximum responses are sought while preserving the converters' structural integrity. Second-order nonlinear formulations still requires further study, as do higher-order nonlinear vertical motions and internal flows.

Regarding the mooring in shallow water, conventional chain catenaries are not good at absorbing dynamic loads. This problem has been identified by some researchers, who pointed out that synthetic ropes have advantages in absorbing large dynamic loads induced by waves. More research is needed to understand and characterize the advantages and disadvantages of the synthetic and hybrid mooring lines for the mooring of WECs, in particular with regard to fatigue life when compressive loads occur, protection against marine grows and sand particles ingress between the fibres.

The development of converter farms requires particular attention to the multi-bodies' interferences in terms of response and power take-off and environmental impact in terms of modified currents, wave fields acting onsite and on the coast, and sedimentary effects. There are no published works on the design of the mooring system for arrays of wave energy converters. This problem needs to be addressed because, in the future, these devices will work in arrays. The development of a full-scale industrial system and "wave hubs" needs reliable instrumentation for environment and structural monitoring.

4. TIDAL ENERGY

4.1 Introduction

The tidal flow of sea water caused by planetary motion is a potential source of energy if suitable systems can be designed and operated in a cost-effective manner. The available methods of extracting energy from tidal movement are classified into devices that store and release potential energy and those that capture kinetic energy directly. The methods of energy extraction and the importance of local site bathymetry and tidal range are described in ISSC (2006). Recent developments for offshore application have concentrated on low-head (kinetic energy) devices as opposed to the estuary-based storage solution of a tidal barrage. This report continues with this emphasis and considers the main developments in tidal current energy systems since the previous report was compiled. It is worth noting that the 240MW tidal barrage scheme at La Rance, France celebrated its 40th year of successful operation in 2007 (Charlier 2007).

4.1.1 Systems in Operation or Under Development

The development of tidal current energy schemes is evident in the schemes now proposed around the world with a significant scale of schemes now reaching 300 – 812 MW in Korean waters, the Bay of Fundy, Canada (6.6MW), Paimpol-Behat, France (4MW), West Bengal, India (4 MW), Pentland Firth, Anglesey, UK (80.5 MW), and Pouto, New Zealand (200MW). There are other schemes under consideration in the US and Australia. The projected timescales for most of these projects are within 5 to 10 years and demonstrate considerable confidence in the technology. The more advanced proposals typically plan to use variants of Horizontal Axis Tidal Turbines (HATT). Although it is suggested that larger powers can be captured with Vertical Axis Tidal Turbines (VATT), however, typically these are less effective at capturing energy for a given swept area.

At present, the largest commercial grid connected machine is the twin rotor HATT system, installed by Marine Current Turbines in 2008 at Strangford Lough, Northern

Ireland (UK) which has a rated power of 1.2MW. This machine reached full power for the first time in December 2008. Open-Hydro installed a 6m diameter driven rim ducted machine which was connected to the electrical supply grid in 2008 at the European Marine Energy Centre, Orkney, UK, and produced the first UK grid connected power in May 2008. At present, no published data are available with regard to achieved performance for either machine as a function of actual tidal speed.

The ability to propose a viable tidal energy scheme relies on an accurate assessment of the tidal resource at a specific location and detailed knowledge of how the local flow regime varies with depth and over short time scales comparable to the blade rate of rotation (typically 20 rpm or less for 14m diameter machines). This data is required for the specification of the blade strength and fatigue characteristics, as well as the loading imposed on the support structure. Typically, decisions about suitable sites require an overall assessment of a particular coastline or area of sea. It is customary to select sites that are easily connected to either a national electrical grid or ideally have a large user of power nearby.

Bedard *et al*. (2007) summarized the findings of collaborative North American programs into wave and tidal energy developments. Two demonstration plants began operation in late 2006 and 30 permit applications have been made. Figure 9 shows the estimated tidal energy resources. The main conclusion was that regulatory barriers were holding up the widespread application of tidal energy. One of the studies upon which Bedard *et al*. based their findings was Hagerman and Bedard (2006) who looked in detail at the possible energy capture off the coast of Massachusetts. A criterion of a flood or ebb tide surface speed averaging at least 1.5m/s was suggested. Six sites were selected that had sufficient tidal power density. Further consideration with respect to suitable bathymetry, seafloor geology, water depth, utility grid interconnection, maritime support infrastructure, and environment identified a possible site for a 500kW demonstration project. In the UK, Mueller and Jeffrey (2007) prepared a 'roadmap' for installing 2GW capacity of tidal current and wave energy devices by 2020. This consultation exercise is aimed at the necessary policy and technology developments required to achieve this as shown in Figure 10.

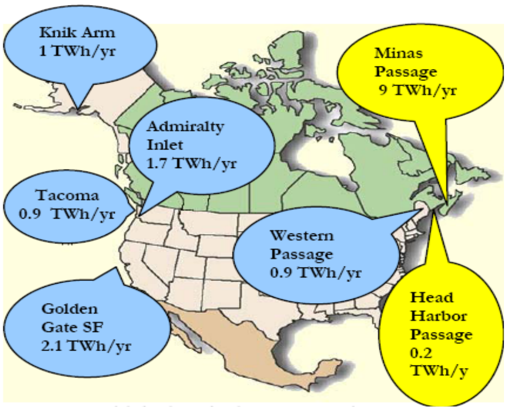


Figure 9: Tidal Electrical Energy estimates for North America from Bedard *et al*. (2007).

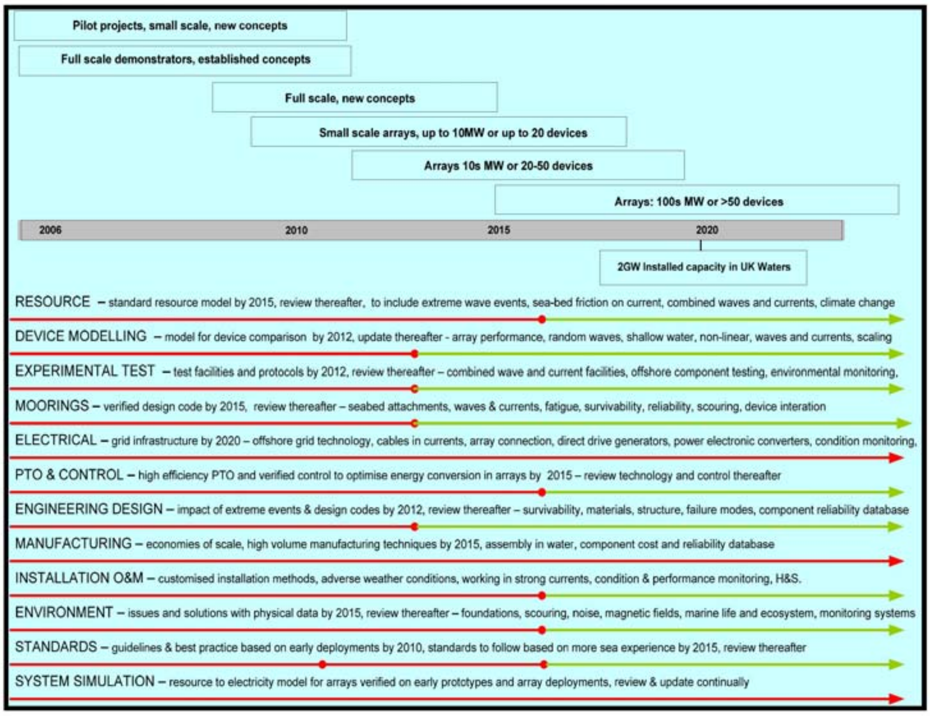


Figure 10: Time dependency between the Technical Strategy and the Deployment Strategy, Mueller and Jeffrey (2007).

4.2 Resource Assessment

A number of papers attempt to assess the energy capacity of specific locations through the development of appropriate theoretical approaches. Blanchfield *et al*. (2007) examined the power potential of Masset sound in Canada. They developed an approach valid for a tidal channel linking a bay to the sea, shown in Figure 12. This uses a one-dimensional model based on the unsteady Navier-Stokes equation applied in the x direction. Flow resistance is applied to the driving tidal wave by the channel surface, the drag of the tidal energy support structure, and the momentum exchange in the tidal energy device itself. The volume flow rate through the channel Q will be influenced by the channel resistance which in turn influences the change in water level in the bay and the net driving head (difference in elevation between open ocean and bay). Applying this model, with the assumption of a constant depth averaged flow rate, it can be shown that as more energy is extracted, the flow rate decreases; and at some stage, increasing the number/size of tidal energy devices will reduce the power capture. For Masset Sound, the maximum average extractable power is approximately 54MW. This would reduce the flow rate through the sound by 40% of the undisturbed flow whereas extracting 12MW would keep the flow rate within 90% of its original value. This work was built on the theoretical developments by Garrett and Cummins (2005) who showed that the average power available in a channel over a semi-diurnal tidal flow, either between an island/mainland or ocean/bay, was between 20 and 24% of the peak tidal pressure head multiplied by the undisturbed mass flux through the channel. This maximum power was independent of the location of the tidal devices, in this case, applied as fences (local arrays of turbines).

Brooks (2006) looked at the tidal stream energy resource in Passamaquoddy-Cobscook Bays. This has a large tidal range of 5.7m and was the proposed location of a tidal barrage scheme estimated at up to 1GW. For tidal stream devices to achieve even a small fraction in such a site, they have to be located in areas of natural flow constriction, which raises the local flow speed. A numerical model with a 300-m x,y grid resolution and ten cells in the vertical direction was used to assess the likely estuarine and coastal flow circulation. The finite difference model examines velocity, temperature, and salinity fields for mass and momentum conservation. This was used to determine the power density with the highest value of 10 kW/m2. In this model, the influence of the tidal device itself was not accounted for. Chang (2008) carried out a detailed study using a 2-D finite element model, also in the Bay of Fundy, and compared barrage and tidal stream energy capture. The predicted water levels were compared with tidal gauge observations. The cost per kWh of the tidal barrage was about half that of the tidal stream, but without the widespread environmental concern for the barrage. Sutherland *et al*. (2007) used a 2-D finite element model with turbines simulated in certain regions by increasing drag within Johnstone Strait in Canada, and compared this to the predictions with the analytical estimates of Garrett and Cummins (2005). Good comparisons were obtained and an important conclusion is that achievable power for a system that attempts to extract a maximum amount of tidal energy has to aim to minimize any losses associated with drag of the turbine support structure. Care was needed to ensure that turbines were sited such that they did not deflect flow away to the other side of a channel or into another channel. A technical note by Garrett and Cummins (2008) discussed the limits to power and showed that a small number of devices may be the most effective strategy, especially if allowance is made for the drag of the support structure. They propose that the approximate formula for the maximum power P is given by $P = 0.22\rho g a Q_{max}$ in which ρ is the density, a is the amplitude of tidal wave, and Qmax is the maximum flow rate in the absence of energy extraction devices. Garrett and Cummins (2007) examined in detail the interaction between multiple devices across a channel and showed that the Betz limit (Cp=16/27) for maximum efficiency of a turbine in an infinite domain is increased by a factor of $(1 - A/A_c)^{-2}$ in a channel in which A is the device area and Ac is the channel area. This is equivalent to the blockage correction that should be applied to tidal energy turbines tested within a finite width channel (towing tank/cavitation) as described by Bahaj *et al*. (2007b).

One of the interesting aspects of tidal energy is its predictability and, therefore, its reliability. Clarke *et al*. (2006) examined the effect of spatially locating tidal energy devices to determine the base load of the power supply. As each device would reach its maximum power at different times, the power generated would become more uniform. They considered a generic device with power proportional to the cube of the instantaneous flow speed and operating at a constant Cp condition of 0.4 between cutin speed and rated power. They assumed three sites were used around the Scottish coast. Figure 11 shows the total power, which always generates nearly a third of the maximum. However, such a scheme will not smooth out the usually significant variations in power between spring and neap tides. Hardisty (2008) examined a larger scale scheme with tidal stream devices installed in the Clyde, Tees, Humber, Severn, Menai Straits, and the Mersey around the coast of the UK that can provide a more or less regular and continuous supply of 45MW for an installed capacity of 200MW.

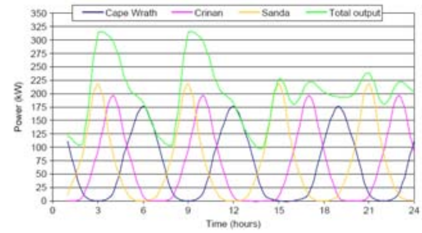


Figure 11: Site and aggregate power output for a 10m diameter tidal turbine with no limiting capacity in spring tides, Clarke *et al*. (2007).

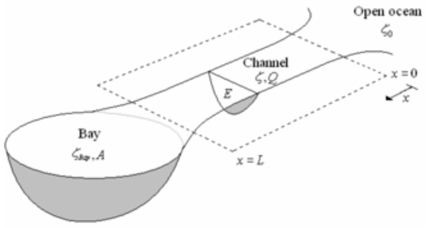


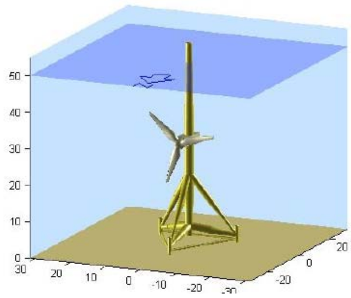
Figure 12: Schematic of a channel linking a bay to an open ocean, Blanchfield *et al*. (2007).

4.3 Environmental Conditions and Loadings

The European Marine Energy Centre (EMEC) is now established to provide a site to test grid connected wave and tidal devices. Norris and Droniou (2007) discuss the development of Acoustic Doppler Current Profiler (ADCP) methodologies for characterizing the tidal flow at their five tidal berths. These are in depths of 25-30 meters and experience strong tidal streams through the Fall of Warness, SE-spring (3.5m/s), NW (3.34 m/s).

A three-bladed 350-mm model scale turbine was investigated by Barltrop *et al*. (2006) in a towing tank with imposed waves. One of the blades was fitted with strain gauges and the blade root bending moment was compared with that predicted by a modified blade element momentum (BEM) code that includes wave velocity based on linear theory. In steep waves, the bending moment was under-predicted. The blade bending moment fluctuates by up to 50% for out-of-plane and 100% of in-plane mean moments. Masters *et al*. (2007) modified an open-source wind turbine BEM code to include the spatial effects of waves superimposed on a typical turbulent boundary layer velocity profile. Other effects incorporated include turbine yaw and teeter and it is proposed that it could be used to assess blade fatigue. Blunden *et al*. (2008) examined the effect of yaw of HATT energy capture using experimental towing tank measurements. These confirmed the momentum theory that predicts that yawed flow reduces power in proportion to the square of the cosine of yaw angle squared and thrust is proportional to cosine of yaw. Whelan *et al*. (2007) considered the influence of the free surface, seabed, and wave- induced velocities on a transverse array of HATT both theoretically and using open channel flow results. The free surface head drop, due to the presence of the turbine and the effective blockage, is described.

McCann (2007) carried out a parametric study of the fatigue loading experienced by a HATT and support when exposed to a time-varying tidal current with a given level turbulence intensity (0-12%) and separately, a range of surface sea state (HS/Tp, 1.5m/7s to 6.0m/28s). The generic 2MW, three-bladed turbines were analyzed using a series of commercial codes developed for similar analysis for wind turbines and modified for tidal current. A von Karman spectral density was used for the turbulence intensity and a JONSWAP wave spectrum. Figure 13 shows the generic turbine and its first structural mode shape. Tables 1 and 2 show the variation in the blade root out-of-plane bending moment, damage equivalent loads for 20 year 1x107 cycles. It is concluded that both wave action and turbulence intensity need consideration as part of the design process.



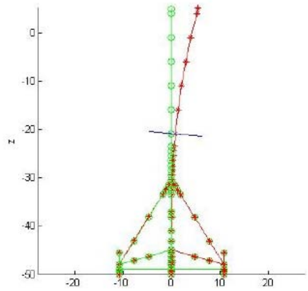


Figure 13: (a): ISO view of generic tidal turbine. (b): First structural mode shape (1.49Hz), McCann (2007).

Table 1
TI Blade Root My DEL [kNm] vs TI (Hs=0m).

	Turbulence Intensity [%]				
m	0	5	7	10	12
4	384.4	708.8	957.9	1219.2	1468.5
6	445.0	885.5	1238.9	1626.9	1978.7
8	483.2	1025.0	1481.3	1988.3	2439.3
10	509.5	1136.5	1682.6	2283.2	2813.6
14	543.3	1300.2	1979.4	2705.4	3348.1

Table 2
Wave height effect on Blade Root My DEL [kNm] vs Hs (TI=10%), McCann (2007).

	Significant wave height [m]			
m	1.5	3.0	4.5	6.0
4	1234.1	1580.6	1849.9	2033.8
6	1602.8	1966.2	2272.6	2472.0
8	1929.1	2278.0	2597.1	2792.3
10	2205.7	2539.9	2860.9	3049.7
14	2627.9	2961.9	3273.2	3467.7

4.4 Stochastic Response

The dynamic environment experienced by a tidal energy device and its support structure is due to spatial and temporal variation in tidal speed. These will be the primary variations about the slowly varying tidal flow speed whose magnitude and local direction vary with the phase of various planetary motions at a given latitude. The resonant motion at a given location is controlled by the local/regional bathymetry. At sites of interest for tidal energy the contraction of available cross-sectional area results in a combination of increased tidal range and tidal flow rate. This is controlled by changes in depth and contractions imposed by islands, in estuaries or channels and sounds. In addition, the surface wave environment driven by the wind environment will impose a velocity variation with depth and movement of the local sea surface elevation. At a given site there will be a correlation between typical weather conditions and the local tidal flow directions. The alignment of devices will result in a wind-imposed fluctuation in the axial and cross-flow directions, which will vary with depth. The local upstream bathymetry will control the depth variation in mean tidal flow and the variation in turbulence intensity.

A preliminary study by Gant and Stallard (2008) examined how the Synthetic Eddy Model (SEM) of Jarrin *et al*. (2006) changes the unsteady tidal turbine wake development, downstream from a porous disc, using Computational Fluid Dynamics (CFD). Figure 15 indicates the variation in axial flow speed. A more rapid recovery of the wake can be seen, creating implications for the positioning of further downstream devices. The dynamic response of a tidal energy device will be more important for tethered devices. Van Zwieten *et al*. (2005) considered the response of 'C-Plane'. A mathematical model is used to represent the 1/30th scale model as a rigid body with moveable control surfaces moored with three linear elastic cable elements. Figure 14 shows the HATT, which use the lateral control surfaces to change depth in order to track the location of maximum ocean (rather than tidal) currents. The model includes gravitational, buoyancy, hydrodynamic cable, gyroscopic, and inertial forces in the dynamic model. The results indicate that the system is stable and can change depth under control..

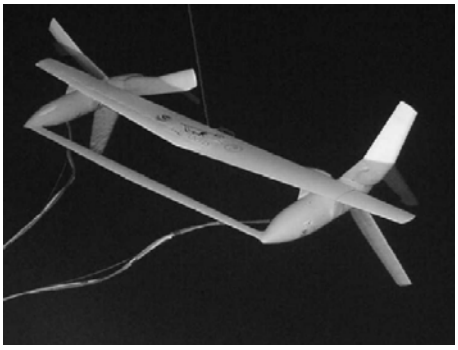


Figure 14: Aquantis 1/30th scale C-Plane prototype in position for a tow test.

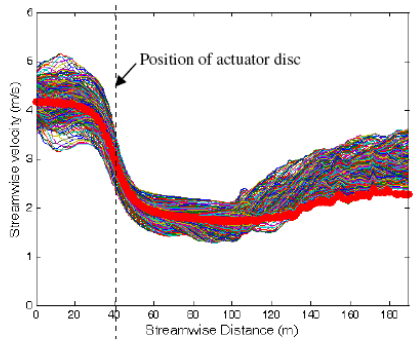


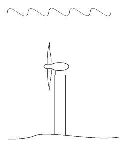
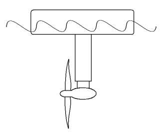
Figure 15: Streamwise velocity along horizontal axis through the centre of the actuator disc; thin multi-colored lines; unsteady SEM; thick red line; steady results, Gant and Stallard (2008).

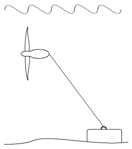
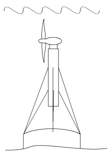
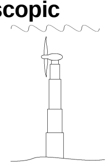
4.5 Structural Response

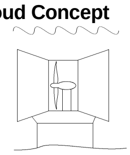
Difficulties and challenges are faced when deploying, maintaining, and recovering equipment within a fast flowing tidal stream. The thrust on a marine turbine of a given rated power is typically three times greater than that experienced by a wind turbine of the same rated power, even though the marine turbine will be significantly smaller. Therefore, there is a major structural problem inherent in holding the rotor securely and reliably in place in the harsh and corrosive sub-sea environment. Several different concepts for the fixing of tidal energy extraction devices are under consideration with varying opinions on each. These range from pile-mounted devices to moored devices, those weighted to the sea bed, and semi-submersible designs. Table 3 gives a brief overview of some of the support structure concepts and provides the main advantages and disadvantages of the designs developed in Nicholls-Lee and Turnock (2008) from Orme and Masters (2006). Clarke *et al*. (2007) estimated the proportion of costs associated with device mooring/mountings, which amount to 33% for the steel and 16% for installation.

As shown by McCann (2007), the design of the blade will be most sensitive to variations in environmental loading. Uzawa *et al*. (2007) examined the use of composite blades for tidal turbines. They suggested that they are the most attractive material for use, but gave a note of caution with respect to their poor cavitation erosion performance. Nicholls-Lee and Turnock (2007) considered the use of a passive adaptive pitch design using the flexible response of composite structures to enhance energy capture and showed reasonable improvements.

Table 3
Possible support structures with advantages/disadvantages.

Support Structure Concept	Advantages	Disadvantages
Pile Mounted  A tower is built on the seabed which supports the rotor at a predetermined depth.	• Stiff structure able to withstand complex loadings • Not subject to wave action • No visual impact • Low collision risk	• Minor maintenance requires complete removal of nacelle. • Additional navigation marks required as no surface component present. • Unable to rotate turbine into flow • Difficult and costly to install
Moored  The turbine is mounted underneath a moored, floating platform on the surface.	• Low cost installation and construction • No need for additional navigational markers • Minor maintenance possible at the site • Can be used in waters of any depth	• Subject to weather and wave effects • Structure flexible and susceptible to fatigue in complex loading situation • Cannot yaw into flow • Surface piercing hence an eyesore and increased collision risk

Tethered  A buoyant system anchored to the seabed via a cable or rigid arm.	• Low cost installation and construction • Can be used in deep water • Self aligning to flow • Not subject to wave or visual impact • Low collision risk	• Maintenance is difficult and costly • Structure flexible and susceptible to fatigue loads • Additional navigational markers required • Fewer devices can be installed in one area
Sheath System  Surface piercing tower installed on the seabed. The rotor and generator are mounted on a sheath and moved up and down mechanically.	• Electrical components above water • Minor maintenance possible at the site • Stiff structure can withstand complex loadings • No additional navigational markers required	• Surface piercing hence an eyesore • Increased shipping collision risk • Subject to weather and wave action • Structure installation costs increase with depth of water • Hoist mechanism exposed to marine corrosion and growth • Unable to rotate turbine into flow
Guyed Tower  The buoyancy of the nacelle is used to tension multiple chain anchors	• Low cost structure • Easily adapted for deeper waters • Not subject to wave and weather actions • No visual impact • Low collision risk	• Minor maintenance not possible on site • Flexible structure vulnerable to fatigue loads • Additional navigational markers required • Unable to rotate turbine into flow • Installation difficult and thus costly
Telescopic  A system of telescopic towers is used to maintain the turbine at the required depth for operation.	• Minor maintenance possible at site • Stiff structure can withstand complex loading situation • Not subject to weather and wave actions • No visual impact • Low collision risk	• High design and construction costs • Additional navigational markers required • Unable to rotate turbine into flow • Construction costs increase markedly with increase in water depth.

Shroud Concept  A cylindrical shroud or duct surrounds the rotor, the middle section of which can be separated for removal and maintenance. The device weight and use of anchor chains fixes it to the seabed	• No yawing mechanism required • Stiff structure able to withstand complex loading • Can be positioned in deep waters • Not subject to weather and wave action • No visual impact • Low collision risk	• Minor maintenance not possible on site • High cost of materials and construction • Additional navigation markers required • Vulnerable to marine fouling as shroud remains in place for life of turbine • Greater exposure to ocean bottom boundary layer decreasing flow speeds

4.6 Interaction between Multiple Arrays of Devices

In order to make significant contributions to energy, arrays of tidal energy devices are required. An important consideration on the loading regime experienced by tidal energy devices is the arrival of any upstream device wake-induced effects. Bahaj *et al.* (2007c) attempted to characterize the wake of a HATT using a momentum approach with a porous disc and associated flow field measurements downstream in a tilting flume. Figure 16 shows the influences on wake and Figure 17 shows the measured mean velocity deficit at different distances downstream. An experimental study of the interaction between multiple arrays is reported by Jo *et al*. (2007). They used a circulating water channel and twin small propellers as proxies for turbines and placed them at different transverse, longitudinal, and diagonal spacings, and measured their rpm as a way of assessing the interaction. Myers and Bahaj (2007) used a 0.4m diameter (1/30th scale) HATT in a circulating water channel to measure the downstream water surface elevation. Antheaume *et al*. (2008) considered the efficiency of vertical axis tidal turbines (VATT) in isolation and when located in an array. They used a CFD code coupled with an inner domain, representing the effect of a VATT through a methodology, to insert momentum sources based on blade element analysis within a cylindrical domain. Figure 18 shows the values of axial velocity on a horizontal plane on a barge arrangement of five VATT turbines. Performance gain studies were carried out for multiple turbines stacked vertically and transversely for different spacings. Although no account was taken of the effect of the necessary support structure, the approach is valuable for generating the best arrangement and also in helping to understand the effect on the downstream wake. Myers *et al*. (2008) examined the effect of the proximity to the seabed and free surface in a tilting flume, again for a porous disk, and with support from an established wind turbine 3-D eddy viscosity numerical model. In the experiment, an Acoustic Doppler Velocimeter ADV was used to measure flow properties at 50Hz for sample volumes of 0.15 cm3. Figure 19 shows the centre-plane mean velocity distributions for three different locations of the turbine disk. The comparison of normalized kinetic energy with the numerical model shows some reasonable agreement with the simple numerical model. It is clear that proximity to boundaries will have an effect on the mean velocity and turbulence intensity that will be important for downstream devices. Sun *et al*. (2008) used a commercial CFD code to examine the downstream wake with a free surface based on a volume- of-fluid approach but without validation against experimental data. A porous disk was used to represent the turbine drag.

Wang, *et al*. (2007) used a cavitation tunnel to observe cavitation patterns at pre-stall, stall, and post-stall HATT operation and for two depths of submergence. Noise levels were measured for the same condition. It was shown that in shallow depth, unstable sheet and cloud cavitation can occur and that these increased the noise levels. Field velocity measurements indicated that the wake may have an impact (scour) on the seabed if the turbine is positioned too close.

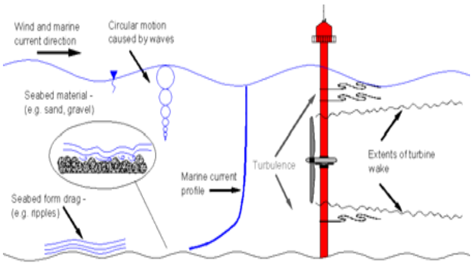


Figure 16: Schematic showing influences on wake of turbine, Bahaj *et al*. (2007c).

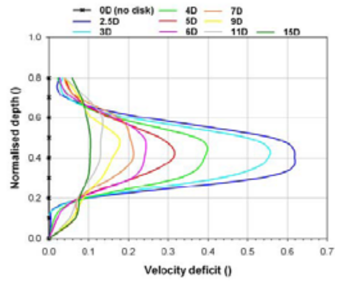


Figure 17: Measured vertical velocity deficit profiles downstream of a porous disc with
$C_t = 0.95$, $U_0 = 0.333$m/s (depth averaged) F_r. = 0.171.

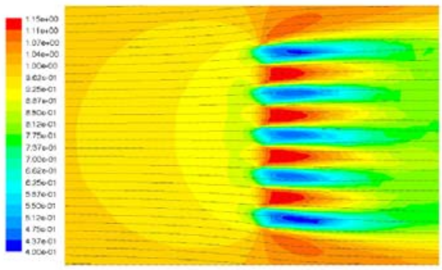


Figure 18: Velocity streamlines in the barge region colored with the reduced velocity $V_X = V_0$; two turbines diameter spacing between turbines, Antheaume *et al*. (2008).

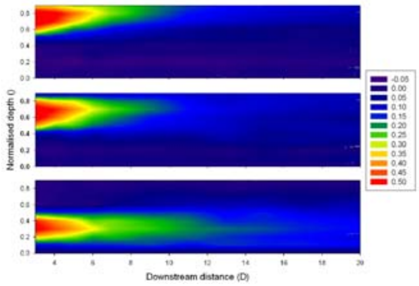


Figure 19: Centre plane velocity deficits for varying disk submersion depths. Disk centre at 0.75d (top); 0.66d (centre); and 0.33d (bottom), Myers *et al*. (2008).

4.7 Influence of Load Take-off

The load applied through the electrical generator and how this is controlled will have an important influence of the dynamics of the interaction between the rotating blades and the support structure. One of the difficulties of energy capture for a submerged system is the necessity to have mechanical components such as a gearbox, nacelle yawing mechanism, and blade pitch. Each of these components will have an effect on the availability of the system through influence on reliability and requirements for maintenance, which will be important for the economic viability of the device, as described in DTI (2007). Nilson *et al*. (2007) looked at removing some of these availability problems by designing a direct drive permanent magnet. Mueller and Jeffrey (2007) also proposed a similar system for a VATT. Ben Elghali *et al*. (2007) developed a time-dependent simulation using Matlab Simulink to investigate the dynamic loads through applying pitch and speed control to a combined turbine and generator system. The simulation was investigated based on the site characteristics at Raz de Sein, France, with the tidal turbine represented using a BEM approach.

4.8 Design of Tidal Energy Converters

To some extent, the design capabilities for tidal turbines have matured rapidly since the 16th ISSC. The following sub-sections capture some of the more significant publications with respect to possible design tools and associated model scale assessment. Presently, due to commercial sensitivities, no full-scale performance has been published in a form that can be used to assess design approaches. Although there are still new concepts proposed, the activity in this area is limited to small model scale devices and theoretical proposals for anything other than HATT and VATT. Work is still ongoing in oscillatory foil systems but with little published information.

4.8.1 Horizontal Axis Tidal Turbines

The recent developments in these systems are associated with gains in performance, improved robustness and reliability, and methods of operating/maintaining the design. An advanced concept is the contra-rotating HATT as proposed by Clarke *et al*. (2007). They used towing tank tests of a 0.82m diameter model scale and 2.5m diameter demonstrator which has been tried at sea. The use of in-line rotors removes the necessity for the structure to resist the driving torque as the downstream rotor generates torque in the opposite direction and of comparable magnitude. This is also achieved with a twin rotor system. Figure 21 shows the demonstrator system and support structure. A combination of a three- and four-bladed system showed reasonable performance but the mechanical system will significantly increase design complexity and the number of components. Detailed towing tank and cavitation tunnel testing, primarily for validation of HATT, Bahaj *et al*. (2007a, 2007b) has helped to quantify the onset of cavitation. Fraenkel (2006) describes the development of the 1MW Seagen and provides performance data for the 300kW Seaflow, as shown in Figure 20.

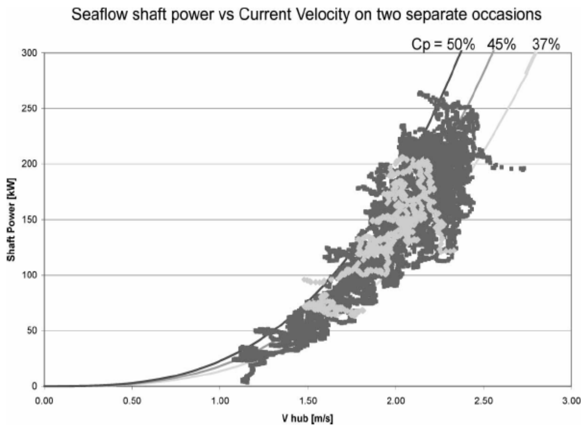


Figure 20: Typical power versus current speed at hub height for two test runs, one at neaps (light grey points) and one at springs (dark grey points), showing underlying calculated curves for three values of CP (based on sampling rate of 2 Hz), Fraenkel (2006).

Figure 21: Demonstrator (CoRMat) on launch vehicle St. Hilda, Clarke, *et al*. (2007).

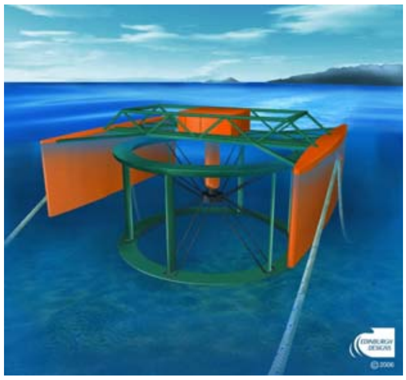


Figure 22: Schematic of Edinburgh Designs proposal with plates to control flow, DTI (2006b).

4.8.2 Vertical Axis Tidal Turbines

Proposers see VATT as a method of increasing the power capture of a single machine by removing the restriction of a finite depth and allowing power to be taken from a larger width. There is little information as to how this greater loading will be resisted by the support structure, or through the blades themselves. The flow regime experienced by each blade is inherently more dynamic, even with blade pitch control, as they are continually changing their orientation to the onset flow, and like helicopter blades, pass through the downstream wake of other blades. Shiono *et al*. (2007) examine the power characteristics for a VATT (Darrieus type) for powering a navigation buoy in the Akashi Strait. Laboratory tests and trials data from the full-scale device are reported with the device providing 110Wh per day. Laboratory tests by Rawlings *et al*. (2008) describe the use of end plates to improve the laboratory scale performance of a three-bladed VATT, and this follows on from their initial numerical and experimental study of a ducted VATT, Klaptocz *et al*. (2007). Schonborn and Chantzidakis (2007) describe the hydraulic pitch control mechanism for a VATT. Torii *et al*. (2007) carried out laboratory and sea trials of a floating VATT and achieved a measured Cp of 0.35 in real sea conditions.

A detailed design investigation, DTI (2006b), shown in Figure 22, by Edinburgh Design, suggests that there may be an economic benefit compared to a HATT. The work includes the use of a BEM approach, CFD, and a structural analysis of the mooring system. Gretton and Bruce (2007) investigated the discrepancies in their BEM approach and suggest that one cause may be uncertainty with the 2-D foil data used. Alidadi *et al*. (2007) compared experiments and numerical approaches for 2-D flow through a VATT using a RANS and discrete vortex method. Salter and Taylor (2007) give a detailed assessment and design for the use of large VATT in Pentland Firth. They suggest a seabed attachment suitable for rapid installation using a tri-link mechanism with rigid legs made from post-tensioned concrete for a 140m diameter rotor with 20 blades. The suitability of ducts to enhance performance was studied by Alidadi *et al*. (2008), using a numerical analysis, with one of the benefits seen to be a method of providing buoyancy and a method to moor. A similar approach, using seabed-mounted vertical plates acting to concentrate the flow using a contraction/diffuser approach, was tested by Ponta and Jacovkis (2008), although they identify one of the uncertainties being the extra construction cost compared to the gain in power capture.

4.8.3 Computational Design Tools

BERR (2008) describes the development of a design tool for tidal stream devices. This tool aims to include blockage effects on a blade element momentum (BEM) analysis, prediction of cavitation, environmental effects (current, waves, turbulence), support structure, and buoyancy effects on the blades. Results were validated against the extensive series of model scale tests at the University of Southampton, Bahaj *et al*. (2007a, 2007b). More detailed analyses of the hydrodynamic performance have been attempted which are ordered below in increasing computational cost. Such approaches are comparable to those used for wind turbines or marine propellers.

1. Blade Element Momentum: balances the sectional performance of each element with momentum change (axial/angular) in a stream tube, BERR (2008), Batten *et al*. (2006), DTI (2007), Grant and Stallard (2008).
2. Lifting Line (LL): Falcao de Campos (2007) describes the application of a vortex lattice approach with a viscous drag correction incorporated as a method of generating optimum chord and pitch distributions.
3. Boundary element or Surface Panel (SP) method: uses a potential flow analysis based on Green's function. Baltazar and Falcao de Campos (2008),

DTI (2007).

4. Computational Fluid Dynamics (CFD), or more exactly, solutions to the Reynolds Averaged Navier Stokes momentum equations (RANS): a number of previously mentioned studies have used CFD to assess the effect on the surrounding flow but none in detail to design a HATT. This is due to the computational cost and uncertainty associated with the approach. Nabavi *et al*. (2007) attempted to use RANS for a VATT but came to no definitive conclusions.

4.9 Guidelines and Standards

There has been little published work on the development of certification and standards that can be applied to tidal turbines since 2006. It is expected that as larger scale experience is monitored at EMEC and at Strangford Lough, this will inform the roll-out of arrays of multiple devices for >10 MW scale systems. A UK Maritime Guidance Note, MCA (2008) describes the issues associated with navigation, safety, and emergency response for offshore renewable energy installations. The intention is that these are used as part of the consent process with respect to site locations, structures and safety zones, collision avoidance, and safety measures during construction, operation, and decommissioning. Of particular interest is the Annex that deals with the specification of the least depth of immersion of current turbine blade; however, no value is specified, as this will relate to the restrictions on marine craft that are allowed to operate in the restricted waters close to the offshore renewable energy installation.

The European Marine Energy Centre has developed an assessment of performance for tidal energy schemes (Swift 2008). Its intention is to provide a uniform methodology for consistent and accurate measurement and analysis for the performance of tidal energy devices. The methodology is presented within the framework of many existing IEC standards. It specifies what information is required about the site, the actual tidal current experienced, how close the measuring device is, the measuring interval, the wave environment, and other factors. As part of device development, the expected stages of decommissioning devices have been given to the UK as guidance notes (DTI 2006).

4.9.1 Environmental Impact

It is expected that in gaining consent for a particular scheme, the developers will need to demonstrate that the installation, operation, maintenance, and decommissioning of the systems have only a limited environmental impact. One component of the process is an understanding of the life-cycle assessment of the complete tidal energy device. Douglas *et al*. (2008) considered the manufacture, installation, operation, and eventual decommissioning of the marine current turbine installed at Strangford Lough. They considered the life-cycle energy and carbon dioxide (CO2) performance. They found, using conservative estimates, that the CO2 emissions at 15g/kWh was comparable to that for land based wind turbines and significantly less than fossil fuel energy production (400-1000 g/kWh). Energy payback was estimated at 14 months and CO2 payback at 8 months. A main area in which further improvements can be made is the structural efficiency and the use of alternative installation methods. The use of a monopole system results in a significant amount of steel having to be left embedded in the seabed with a concrete cap. This presently is the problem with all monopile structures and may be a reason to consider tripod-type structures, which require three pile connections that are much smaller. The assessment considers the likely energy capture, shown in Figure 23, and quotes an expected availability of 90%. The materials used and manufacturing process are considered, as well as transportation to the site. The mass breakdown indicates that steel makes up 89%, iron 7%, composites 2%, copper 1%, and other materials 1%. The steel tower is 54.6m tall and extends above the sea surface to allow access to the turbine structure which can be raised out of the water. The main composite components are the two blades on each of the twin rotors that are joined to the monopile via cross beam. About half of the tower will remain embedded in the seabed.

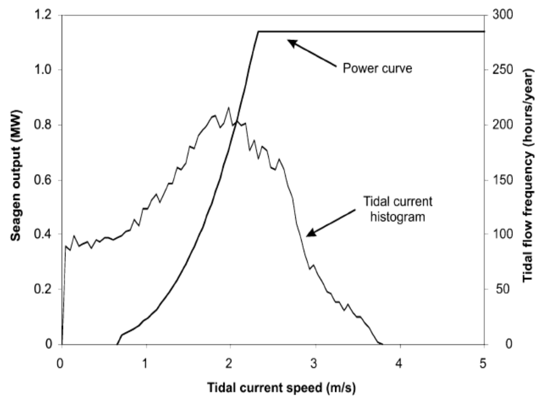


Figure 23: Tidal current histogram for Strangford Narrows and Seagen power curve, Douglas *et al*. (2008).

4.10 Needs in Terms of Research

The future of tidal energy would appear to be attractive as a reasonably cost-effective source of renewable energy. It is apparent that there is still no consensus as to a favored machine topology with both HATT and VATT concepts receiving considerable investment in research and development. Although, it is worth noting that presently, only HATT machines are deployed at a commercial scale. One area of weakness is the systematic assessment of the necessary capabilities of support structures. Highlighted in the life-cycle assessment of Douglas *et al*. (2008), there are still possible improvements that can be made. Apart from the conference paper of Orme and Masters (2006) that qualitatively assessed concepts, no rigorous analytic approach has been applied to possible approaches. The requirement to minimize drag of support structures in large-scale schemes is likely to lead the design path for such structures along possibly different avenues to those used for offshore wind turbines.

Significant progress has been made in assessing the influence of variable environmental loading due to turbulence and sea state. Presently, there is no pubic domain data relating to the actual dynamic behavior experienced by full-scale machines. It is likely that a crucial component will be the composite blade design, as this component will experience the most extreme load variations and it will need to survive an order of 1x107 load cycles. As large amounts of energy can also be produced by the use of an array of many devices, ideally closely situated as much as possible to reduce cabling costs, quantification of the interaction effects of an upstream wake on tidal turbine performance still requires further investigation. The measurement of the full-scale wake of an actual turbine would provide valuable design data alongside more detailed CFD analysis, and model scale tests of systems that represent more of the actual turbine wake effects than just a porous disk. The developments in assessing the interaction between an array of turbines and how this modifies the flow rate through the turbines and overall, through a given channel, sound, or estuary, will be a crucial requirement for gaining consent with respect to environmental impact.

5. SUMMARY AND CONCLUSIONS

The development of offshore wind turbines on fixed support structures has relied heavily on the past experiences with land-based turbines and traditional oil and gas installations. This has made the path to success relatively short for installations in shallow waters, i.e. up to 25 meters water depth, applying steel monopile structures and concrete gravity foundations as the commonly used substructures. The major difference from traditional fixed offshore structures is the dominant dynamic response behaviour and the combined action of wind and waves which govern the response. Both simulation tools and design rules to address this have been devised and refined over the period since the previous ISSC report. This is manifested in the publication of an international standard as discussed in detail above. However a number of optimisations and design issues are still left to be dealt with before it can be truly said that a fully developed technology has emerged. For instance the behaviour of monopiles in lateral loading is not understood to a sufficient degree of detail to allow for optimisation, i.e. design to the limit. Investigations have been made during the course of development, but ongoing research projects are still devoted to this subject. The next step is, as the economical feasibility improves, to move to waters deeper than 25 meters. A demonstration project at 45 meters water depth with a space frame substructure similar to traditional fixed offshore structures has been designed and put into operation. In going to even deeper waters floating support structures seems to be an option to consider. This opens a whole new variety of challenges as dynamic response becomes even more complicated. There is in this field also a considerable amount of experience to pull on regarding floaters, however, the control behaviour of the turbine has to be reconsidered to ensure stability in response. Though this field is far from having matured to the same level as fixed supported wind turbines at shallow waters a prototype is soon to be put into operation in Norwegian waters.

There are dozens of Wave Energy Converter (WEC) concepts proposed and investigated, and several prototypes tested or under testing, however at this moment it is not clear which will prevail. Contrary to the wind sector, the wave energy sector is characterized by the diversity of concepts and the fact that none has proved yet to be technically and economically viable. The tendency nowadays seems to be for near shore floating devices, since the waves are more energetic here than along the shoreline.

The development and assessment of the wave energy converters (WECs) are closely linked to the fields of offshore and coastal engineering. The methods and results developed within these fields are essential to further development of the WECs. The main difference is that most WECs are designed to operate with large motion response, usually at resonance, while for normal offshore structures resonant response is to be avoided. A further design challenge is the need for large energy absorption at moderate sea-states combined with survivability in extreme sea-states. Few dedicated guidelines for WECs have been proposed by the certifying bodies. Presently, mainly DNV offers such a guideline for design. However, guidelines for design of offshore and coastal structures are useful also for design of WECs, taking the special WEC features into due consideration. In addition to the increased technological knowledge about WEC design and efficiency, it is foreseen that environmental aspects, such as sediment transport, living resources and decommissioning will have increased focus in the future.

To assess design loads for WECs, hydrodynamic models based upon first principles and site specific statistics of the waves, wind and current should be used. Model testing to verify survivability are recommended as a supplement to numerical studies. The guidelines developed for the offshore industry can be used as a guide for deciding load combinations and relevant safety factors. Fatigue loads can in principle be determined by the techniques used in the offshore industry.

The recent developments in tidal turbine technology offer a reasonable degree of confidence that this technology will make an important contribution to the generation of renewable energy when applied to appropriate sites. It is still unclear what will make the most effective type of generation device and likewise the most appropriate structure. The ability to make design decisions which will ensure that the eventual devices are cost-effective yet have a minimal impact on the environment remains an important factor. In order to achieve large-scale power generation capability, arrays of tidal devices will be required. This will require a detailed assessment, for each specific site, of the interaction between the number (and type) of device, their location relative to each other and most importantly, their impact on the local tidal conditions. For such tidal turbine array systems, it is clear that minimizing the drag of the support structure will be an important feature of the design. As a result, the use of ducts (or shrouds) is likely to only benefit isolated tidal turbines. The assessment of a specific resource needs to consider the local flow environment, including the velocity variation with depth and turbulence intensity and any possible influence of the wave environment. This report has identified the need to develop specific support structure arrangements that are well suited for use with tidal turbines. These structures have to facilitate installation, operation, maintenance, and eventual decommissioning without imposing higher costs. The certification methodologies developed for offshore wind turbines should provide a suitable framework for moving to large-scale applications of this technology.

ACKNOWLEDGEMENT

The Committee gratefully acknowledges the extensive editorial assistance provided by Joshua Goldstein and Krista Reddington. Additionally, the Committee thanks Zakoua Guede from Ifremer.

REFERENCES

Achmus, M., Abdel-Rahman, K., Wörde, F.T. (2007). Geotechnical Design of Piles supporting Foundation Structures for Offshore Wind Energy Converters. *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference* Lisbon, Portugal, July 1-6.

Agarwal, P. and Manuel, L. (2007a). Simulation of offshore wind turbine response for extreme limit states. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering,* OMAE2007-29326.

Agarwal, P. and Manuel, L. (2007b). Empirical wind turbine load distributions using field data. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering* OMAE2007-29327.

Agamloh, E.B., Wallace, A.K. and von Jouanne, A. (2008). A novel direct-drive ocean wave energy extraction concept with contact-less force transmission system. *Renewable Energy*, 33:3, 520-529.

Alidadi, M., Nabavi, Y., Calisal, S. (2008). The effect of ducting on the performance of a vertical axis tidal turbine, *Proceedings of OMAE*, Estoril, Portugal, OMAE2008-57902.

Antheaume, S., Maıtre, T., Achard, J-L, (2008). Hydraulic Darrieus turbines efficiency for free fluid flow conditions versus power farms conditions, *Renewable Energy* 33, 2186–2198.

Ang, A. and Tang, W. (2007). Probability concepts in engineering, *Wiley 2nd edition*.

Babarit, A., Clément, A.H. (2006). Optimal latching control of a wave energy device in regular and irregular waves. *Applied Ocean Research*, 28:2, 77-91.

Babarit, A., Ben Ahmed, H., Clément, A.H., Debusschere, V., Duclos, G., Multon, B., Robin, G. (2006). Simulation of electricity supply of an Atlantic island by offshore wind turbines and wave energy converters associated with a medium scale local energy storage. *Renewable Energy*, 31:2,153-160.

Bahaj, A.S., Batten, W.M.J., G. McCann, G. (2007a). Experimental verifications of numerical predictions for the hydrodynamic performance of horizontal axis marine current turbines , *Renewable Energy* 32, 2479–2490.

Bahaj, A.S., Molland, A.M., Chaplin, J.R., Batten, W.M.J. (2007b). Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, *Renewable Energy* 32, 407–426.

Bahaj, A.S., Myers, L.E., Thomson, M, Jorge, N. (2007c). Characterising the wake of horizontal axis marine current turbines, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Balme, R., Le Saux, K., Ben Elghali, S.E., Benbouzid, M.E.H., Charpentier, J.F., Hauville, F., Drouen, L. (2007). A Simulation Model for the Evaluation of the Electrical Power Potential Harnessed by a Marine Current Turbine in the Raz de Sein, *Proceedings of the Oceans '07 IEEE Conference*, 18-21 June, Aberdeen, U.K.

Baltazar, J., Falcao de Campos, J.A.C. (2008). Hydrodynamic analysis of a horizontal axis marine current turbine with a boundary element method, *Proceedings of OMAE*, Estoril, Portugal, OMAE2008-58033.

Barltrop, N., Varyani, K.S., Grant, A., Clelland, D., Pham, X. (2006). Wave-current interactions in marine current turbines, Proc. *IMechE Part M: J. Engineering for the Maritime Environment.*, 220, 195-203.

Batten, W. M. J., Bahaj, A. S., Molland, A.F., Chaplin, J. R. (2006). Experimentally validated numerical method for the hydrodynamic design of horizontal axis tidal turbines. *Ocean Engineering*, 34, (7), 1013-1020.

Bedard *et al.*, North American ocean energy status - March 2007, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Ben Elghali, S.E., Benbouzid, M.E.H., Charpentier, J.F. (2007). Marine Tidal Current Electric Power Generation Technology: State of the Art and Current Status, *Proceedings of the Oceans '07 IEEE Conference*, 18-21 June, Aberdeen, U.K.

BERR (2008). Development of a design tool for axial flow tidal stream devices, UK Dept of Business, Enterprise and Regulatory Reform, Report No. URN: 08/852.

Bittencourt, C. (2007). Certification of Marine Energy Converters: The Experience So Far. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2007-29258.

Blanchfield, J., Rowe, A., Wild, P., Garrett, C. (2007). The Power Potential of Tidal Streams including a Case Study for Masset Sound, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Blunden, L., Batten, W.M.J., Bahaj, A.S. (2008). Comparing energy yields from fixed and yawing horizontal axis marine current turbines in the English channel, *Proceedings of OMAE*, Estoril, Portugal, OMAE2008-57763.

Boström, C., Lejerskog, E., Svensson, 0., Tyberg, S., Eriksson, M., Bolund, B., Leijon, M., Waters, R. and Savin, A. (2008). Experimental Results From an Offshore Wave Energy Converter. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering*, June 15-20, Estoril, Portugal,

OMAE2008-57415.
Brooks, D.A. 2006, The tidal-stream energy resource in Passamaquoddy–Cobscook Bays: A fresh look at an old story, *Renewable Energy* 31, 2284–2295.
Carbon Trust, (2005). Guidelines on the design and operation of wave energy converters. Commissioned by the Carbon Trust and prepared by Det Norske Veritas.
Chang, J, 2008. Hydrodynamic modelling and feasibility study of harnessing tidal power at the bay of Fundy, PhD Thesis, Civil Engineering, University of Southern California. 160.
Chaplin, J.R., Farley, F.J.M., Prentice, M.E., Rainey, R.C.T., Rimmer, S.J. and Roach, A.T. (2007). Development of the ANACONDA all-rubber WEC. 7th European Wave and Tidal Energy Conference, 11-14 Sep., Porto, Portugal.
Charlier, R.H. (2007). Forty candles for the Rance River TPP tides provide renewable and sustainable power generation, *Renewable and Sustainable Energy Reviews*, 11, 2032-2057.
Clarke, J.A., Connor, G., Grant, A.D., Johnstone, C.M. (2006). Regulating the output characteristics of tidal current power stations to facilitate better base load matching over the lunar cycle, *Renewable Energy* 31, 173–180.
Clarke, J.A., Connor, G., Grant, A.D., Johnstone, C.M., Mackenzie, D. (2007). Development of a Contra-Rotating Tidal Current Turbine and Analysis of Performance, *Proceedings of the 7th European Wave and Tidal Energy Conference,* EWTEC 2007, 11-14 Sep., Porto, Portugal.
Cochin, V., Thomas, N., Mariette, V., Gurgel, K-W. (2006). SURLITOP experiment in West Brittany, France: results and validation. *6th International Radiowave Oceanography Workshop (ROW-6), Hamburg, Germany, 15-18 May*.
Cruz, J. (2008) OceanWave Energy - Current Status and Future Perspectives, *Springer Series in Green Energy and Technology* ISSN 1865-3529.
Douglas, C.A., Harrison, G.P., Chick, J.P. (2008). Life cycle assessment of the Seagen marine current turbine, Proc. IMechE Part M: J. Engineering for the Maritime Environment, 222, 1-12.
DNV (1995). Guidelines for offshore structural reliability analysis.
DTI (2006a). Decommissioning of offshore renewable energy installations under then energy act 2004, guidance notes for industry. UK Department of Trade and Industry. URN 06/2086. 76.
DTI (2006b). Variable pitch vertical axis tidal turbine, UK Department of Trade and Industry, URN 06/929. 83pp.
DTI (2007). Economic viability of a simple tidal stream energy device, UK Department of Trade and Industry, Contract No.TP/3/ERG/6/1/15527/REP.
Falnes, J. (2007) A review of wave-energy extraction. *Marine Structures*, 20:4, 185-201.
Fitzgerald, J., Bergdahl, L. (2008). Including moorings in the assessment of a generic offshore wave energy converter: A frequency domain approach. *Marine Structures*, 21:1, 23-46.
Folley, M., Whittaker, T.J.T. and Henry, A. (2007) The effect of water depth on the performance of a small surging wave energy converter. Ocean Engineering,

34:8-9, 1265-1274.

Fonseca, N., Pascoal, R., Marinho, J., and Morais, T. (2008). Analysis of Wave Drift Forces on a Floating Wave Energy Converter. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering,* OMAE2008-57941.

Fonseca, N., Pessoa, J., Pascoal, R., Morais, T., Dias, R., (1999). Calculation of maximum pressure distributions for structural design of a floating wave energy converter. *Proceedings 2nd International Conference on Ocean Energy*, 15-17 October, Brest, France.

Fraenkel, P.L. (2007). Marine current turbines: pioneering the development of marine kinetic energy converters, *Proc. IMechE Part A: J. Power and Energy*, 221, 159-169.

François, M., Camps, C., Alvarez, J. and Quiniou-Ramus, V. (2007). Multi-variate I-FORM contours for the design of offshore structures (Practical methodology and application to a West Africa FPSO). *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6.

Fukumoto, Y., Moriya, Y., Tsuchiya, K., Hara, M. and Suzuki, H. (2006). A Feasibly Study of Reinforced Concrete Spar-Buoy for Offshore Wind Turbine. *Global Wind Power 2006*, Australia.

Gant, S. and Stallard, T. (2008). Modelling a tidal turbine in unsteady flow, *Proceedings of the Eighteenth (2008) International Offshore and Polar Engineering Conference*, Vancouver, BC, Canada.473-479.

Garrett, C., Cummins, P. (2005). The power potential of tidal currents in channels, *Philosophical Transactions of the Royal Society* A 461, 2563–2572.

Garrett, C., Cummins, P. (2007), The efficiency of a turbine in a tidal channel, *Journal of Fluid Mechanics*, 588, 243–251.

Garrett, C., Cummins, P. (2008). Limits to tidal current power, *Renewable Energy* 33, 2485–2490.

Graw, K.U. (1993). Shore protection and electricity by submerged plate wave energy converter. *Proceedings of the European Wave Energy Symposium*, Edinburg, Scotland, pp. 379–84.

Griet, De Baker, Vantorre, M., Victor, S., Rouck, De Julien, Beels, C. (2008). Investigation of vertical slamming on point absorbers. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering*, June 15-20, Estoril, Portugal, OMAE2008-57962.

Gretton, G.I. and Bruce, T (2007). Aspects of mathematical modelling of a prototype scale vertical-axis turbine. *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Guinot, F., Le Boulluec, M. (2008). Realistic marine flow conditions for current turbines studies.*2nd International Conference on Ocean Energy (ICOE 2008), 15th – 17th October, Brest, France*.

Hagerman, G, and Bedard, R. (2006). Massachusetts Tidal In-Stream Energy Conversion (TISEC): Survey and Characterization of Potential Project Sites, Electrical Power Research Institute EPRI - TP- 003 MA Rev 1.

Hardisty, J. (2008), Power intermittency, redundancy and tidal phasing around the United Kingdom, *The Geographical Journal*, 174, 76–84.

Huertas-Olivares, C., Neumann, F., Sarmento, A., 2007, "Environmental management recommendations for the wave energy Portuguese Pilot Zone", *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

IEC 61400-1,ed.3, (2005). Wind Turbines - Part 1: Design Requirements.

IEC 61400-3 FIDS (2008). Wind Turbines - Part 3: Design Requirements for Offshore Wind Turbines.

Ishihara, T., Phuc, P. V., Sukegawa, H., Shimada, K. and Ohyama, T. (2007). A study on the dynamic response of a semi-submersible floating offshore wind turbine system Part 1 : A water tank test. *Proceedings of the 12th International Conference on* Wind *Engineering*, 2511-2518, Cairns.

ISSC (2006). Report of Committee V.4 Ocean Wind and Wave Energy Utilisation, *Proceedings of International Ship and offshore Structures Congress*, Vol. 2, 165-211.

Jarrin, N, Benhamadouche, S, Laurence, D and Prosser, R (2006). A synthetic-eddy-method for generating inflow conditions for large eddy simulations, *International Journal of Heat Fluid Flow*, 27, 585-593.

Jensen, J. J., Mansour, A.E. (2006). Extreme Motion Predictions for Deepwater TLP Floaters for Offshore Wind Turbines. *The Fourth International Conference on Hydroelasticity in Marine Technology*, Wuxi, 361-368.

Jo, C.H., Park, K.K., Im, S.W. (2007), Interaction of Multi Arrayed Current Power Generations, *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6

Josset, C. and Clément, A.H. (2007). A time-domain numerical simulator for oscillating water column wave power plants. *Renewable Energy*, 32: 8, 1379-1402.

Johanning, L., Smith, G.H., Wolfram, J. (2007). Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. *Ocean Engineering*, 34:14-15, 1918-1934.

Johanning, L., Smith, G.H. and Bullen, C. (2007). Large scale mooring line experiments and comparison with a fully dynamic simulation program with importance to WEC installation. *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6.

Jonkman, J.M. and Buhl, M.L. Jr. (2007). Loads Analysis of a Floating Offshore Wind Turbine Using Fully Coupled Simulation. *WindPower 2007 Conference & Exhibition* Los Angeles, California.

Kerbiriou, M-A., Babarit, A., Prevosto, M., Clément, A.H. and Maisondieu, Ch. (2007) Influence of an Improved Sea-State Description on a Wave Energy Converter Production. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering,* OMAE2007-29254.

Klaptocz, V.R., Rawlings, G.W., Nabavi, Y., Alidadi, M., Li, Y., Calisal, S.M. (2007). Numerical and Experimental Investigation of a Ducted Vertical Axis Tidal Current Turbine, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Klose, M., Dalhoff, P., Argyriadis, K. (2007). Integrated Load and Strength Analysis for Offshore Wind Turbines with Jacket Structures. *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference* Lisbon, Portugal, July 1-6.

Kofoed, J.P., Frigaard, P., Friis-Madsen, E. and Sørensen, H.C. (2006). Prototype testing of the wave energy converter wave dragon. *Renewable Energy*, 31:2, 181-189.

Kühn, M. (2001). Dynamics and Design Optimisation of Offshore Wind Energy Conversion System. PhD thesis, Delft University of Technology, Section Wind Energy. Department of Civil Engineering.

Leijon, M., Danielsson, O., Eriksson, M., Thorburn, K., Bernhoff, H., *Isberg*, J., Sundberg, J., Ivanova, I., Sjöstedt, E. Ågren, O., Karlsson, K.E., Wolfbrandt, A. (2006) An electrical approach to wave energy conversion. *Renewable Energy*, 31:9, 1309-1319.

Lesny, K., and Wiemann, J. (2005). Design Aspects of Monopiles in German Offshore Wind Farms. *Proceedings of the International Symposium on Frontiers in Offshore Geotechnics*, S. Gourvenec and Mark Cassidy eds., A. A. Balkema Publishing, 383-389.

Liingaard, M. (2006). Dynamic Behaviour of Suction Caissons. PhD thesis, Aalborg University, Department of Civil Engineering.

Manabe, H. (2008). “Development of the floating structure for the sailing-type Offshore Wind Farm”, *OCEANS'08 MTS/IEEE KOBE-TECHNO-OCEAN'08*, No.071207-001.

Mackay, E., Retzler, Ch., Bahaj, A. and Challenor, P. (2008) Wave Energy Resource Estimation Using Satellite Altimeter Data. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering,* OMAE2008-57976.

Manabe, H. (2008). “Development of the floating structure for the sailing-type Offshore Wind Farm”, *OCEANS'08 MTS/IEEE KOBE-TECHNO-OCEAN'08*, No.071207-001.

Maritime and Coastguard Agency MCA (2008). Offshore renewable energy installations (OREIs) Guidance on UK Navigational practice, safety and emergency response issues, Marine Guidance Note MGN 371 (M+F).

Masters, I, Orme, J.A.C., Chapman, J. (2007) Towards realistic marine flow conditions for tidal stream turbines, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

McCann, G.N. (2007). Tidal current turbine fatigue loading sensitivity to waves and turbulence – a parametric study, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Ming, H., and Aggidis, G.A., Developments, expectations of wave energy converters and mooring anchors in the UK. *Journal of Ocean University of China (Oceanic and Coastal Sea Research)*, 7:1, 10-16.

Mouslim, H. (2008). SEM-REV Wave Energy Test SEM Site. Project Development. *November 19th – OREG Fall Symposium – Whistler, Canada*.

Mueller, M, Jeffrey, H. 2007. UKERC Marine Renewable Energy Technology

Roadmap, University of Edinburgh, UK Energy Research Centre.

Muller, H., Dumas, F., Blanke, B., and Mariette, V. (2007). High-resolution atmospheric forcing for regional oceanic model: the Iroise Sea. *Ocean Dynamics*, 57:4-5, 375-400.

Musial, W. and Butterfield, S. (2006). "Energy from Offshore Wind". *Offshore Technology Conference*, OTC 18355 (OER), Houston.

Myers , L.E., Bahaj, A.S. (2007). Wake studies of a 1/30th scale horizontal axis marine current turbine, *Ocean Engineering* 34, 758–762.

Myers, L.E., Bahaj, A.S., Rawlinson-Smith, R.I., Thomson, M. (2008). The effect of boundary proximity upon the wake structure of horizontal axis marine current turbines, Proceedings of OMAE, Estoril, Portugal, 2008, OMAE2008-57667.

Nerzic, R., Frelin, C., Prevosto, M. and Quiniou-Ramus, V. (2007). Joint distributions of Wind/Waves/Current in West Africa and derivation of multivariate extreme I-FORM contours. *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6.

Nicholls-Lee, R.F., Turnock, S.R. (2007). Enhancing Performance of a Horizontal Axis Tidal Turbine using Adaptive Blades, Proceedings of the Oceans '07 IEEE Conference, 18-21 June, Aberdeen, U.K.

Nicholls-Lee, R.F and Turnock, S.R. (2008) Tidal energy extraction: renewable, sustainable and predictable. *Science Progress*, 91, (1), 81-111.

Nielsen, A.W., Hansen, E.A. (2007). Time-Varying Wave and Current-Induced Scour Around Offshore Wind Turbines. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering* OMAE 2007-29098.

Norris, J.V., Droniou, E. (2007). Update on EMEC activities, resource description, and characterisation of wave-induced velocities in a tidal flow, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Offshore Center Denmark (2006), Offshore Wind Turbines situated in Areas with Strong Currents. DOC. NO. 6004RE01ER1, February.

Orer, G., Ozdamar, A. (2007). An experimental study on the efficiency of the submerged plate wave energy converter. *Renewable Energy*, 32:8, 1317-1327.

Orme, J.A.C., Masters, I. (2006). Analysis and Comparison of Support Structure Concepts for Tidal Stream Turbines, *Proceedings of World Maritime Technology Conference*. IMarEST, London.

Perdigão. J. and Sarmento, A. (2003). Overall-efficiency optimisation in OWC devices. *Applied Ocean Research*, 25: 3, 157-166.

Phuc, P.V., Ishihara, T. (2007). A study on the dynamic response of a semi-submersible floating offshore wind turbine system Part 2: numerical simulation. *Proc of 12th ICWE 2007*, 959-966, Cairns.

Ponta, F.L., Jacovkis, P.M. (2008). Marine-current power generation by diffuser-augmented floating hydroturbines, *Renewable Energy*, 33, 6650673.

Prevosto, M., Le Louarne, J-F. and Guede, Z. (2007). Statistical Analysis of Low Frequency Motions of Floating Bodies in Shallow Water. *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6.

Rawlings, G.W., Alidadi, M., Klaptocz, V.R., Nabavi, Y., Li, Y, Mikkelsen, J., Calisal, S.M. (2008). Application of end plates for vertical axis hydro turbine performance enhancement. *Proceedings of the Eighteenth International Offshore and Polar Engineering Conference*, Vancouver, CanadaLisbon, Portugal, July 1-6.

Retzler, Ch. (2006). Measurements of the slow drift dynamics of a model Pelamis wave energy converter. *Renewable Energy*, 31:2, 257-269.

Saigal, R. K. , Dolan, D., Der Kiureghian, A., Camp, T. and Smith, C.E (2007). An Assessment of Structural Design Guidelines for Offshore Wind Turbines. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering* OMAE2007-29629, June 10-15, San Diego, California, USA.

Saillard, M., Forget, Ph., Soriano, G., Joelson, M., Broche, P. and Currier, Ph. (2005). Sea surface probing with L-band Doppler radar: experiment and theory Comptes Rendus Physique, 6:6, 675-682.

Salter, S.H., Taylor, J.R.M., (2007) Vertical-axis tidal-current generators and the Pentland Firth, *Proc. IMechE Part A: J. Power and Energy*, 221, 181-199.

Schonborn, A., Chantzidakis, M. (2007). Development of a hydraulic control mechanism for cyclic pitch marine current turbines, *Renewable Energy* 32, 662–679.

Skaare, B., Hanson, T., Nielsen, F.G. (2006). Integrated Dynamic Analysis of Floating Offshore Wind Turbines. *Proceedings of 2006 European Wind Energy Conference and Exhibition*, Athens, Greece.

Skaare, B., Hanson, T., Nielsen, F.G. (2007). Importance Of Control Strategies On Fatigue Life Of Floating Wind Turbines. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*. OMAE2007-29277.

Shim, S., Kim, M.H. (2008). Rotor-Floater-Tether Coupled Dynamic Analysis of Offshore Floating Wind Turbines. *Proceedings of the Eighteenth International Offshore and Polar Engineering Conference*, Vancouver, 455-460.

Shiono, M., Naoi, K, Suzuki, K (2007). Output characteristics of power generation system from tidal currents for a navigation buoy, *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, Lisbon, Portugal, July 1-6.

Sun, X., Chick, J.P., Bryden, I.G. (2008). Laboratory-scale simulation of energy extraction from tidal currents. *Renewable Energy* 33, 1267-1274.

Sutherland, G., Foreman, M., Garrett, C. (2007). Tidal current energy assessment for Johnstone Strait, Vancouver Island, Proc. IMechE Part A: J. Power and Energy, 221, 147-157.

Suzuki, H. and Sato, A. (2007), Load on Turbine Blade Induced by Motion of Floating Platform and Design Requirement for the Platform. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2007-29500.

Swift, R. 2008. Assessment of performance for tidal energy conversion systems, UK

Dept for Business, Enterprise and Regulatory Reform, MRF/02/00008/01/REP, URN 08/1154.

Tarp-Johansen, N.J. (2005). Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects. *Journal of Solar Energy Engineering*, May, 127, 242-252.

Tarp-Johansen, N. J., Manwell, J.F. and McGowan, J. (2006). Application of Design Standards to the Design of Offshore Wind Turbines in the U.S., *Offshore Technology Conference,* OTC 18559.

Tedd, J., Kofoed, J.P. (2009). Measurements of overtopping flow time series on the Wave Dragon, wave energy converter. *Renewable Energy*, 34:3, 711-717.

Thakker, A. and Abdulhadi, R. (2008) The performance of Wells turbine under bi-directional airflow. *Renewable Energy*, 33:11, 2467-2474.

Torresi, M., Camporeale, S.M., Strippoli, P.D., Pascazio, G. (2008) Accurate numerical simulation of a high solidity Wells turbine. *Renewable Energy*, 33: 4, 735-747.

Torii, T., Ookubo, H., Yamane, M., Sagara, K., Seki, K., Sekita, K. (2008). A Study on Effectiveness of Straight-wing Vertical-axis Hydro Turbine Generation System in the Tidal Current, *Proceedings of the Seventeenth International Offshore and Polar Engineering Conference*, 1-6 July, Lisbon, Portugal.

Trumars, J. M.V., Jonsson, J. O., Bergdahl, L. (2006). The Effect of Wind and Wave Misalignment on the Response of a Wind Turbine at Bockstigen. *Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering*, OMAE2006-92075.

Tuomo Kärnä, T. (2006). An Extreme Value Analysis of Local Ice Pressures. *Proceedings of the International Conference Exhibition on Performance of Ships and Structures in Ice*. ICETECH-06. July 16-19.

Uzawa, K., Kageyama, K., Murayama, H., Ohsawa, I., Kanai, M., Nishiyama, T., Shichiri, A.(2008). A study of the characteristic and possibility from applying composite materials to the blades of tidal power generation, *Proceedings of OMAE*, Estoril, Portugal, OMAE2088-57338.

Valério, D., Beirão, P., Sá da Costa, J. (2007) Optimisation of wave energy extraction with the Archimedes Wave Swing. *Ocean Engineering*, 34:17-18, 2330-2344.

1. Van der Tempel, J. (2006). Design of Support Structures for Offshore Wind Turbines. *Ph.D. thesis, Delft University of Technology*, ISBN 90-76468-11-7.
2. Van Zwieten, J., Driscoll, F.R., Leonessa, A., Deane, G (2005), Design of a prototype ocean current turbine—Part I: mathematical modelling and dynamics simulation, Ocean Engineering, 33, 1485-1521.

Vicinanza, D., Frigaard, P. (2008). Wave pressure acting on a seawave slot-cone generator. *Coastal Engineering*, 55: 6, 553-568.

W.E. de Vries, J. van der Tempel, H. Carstens, K. Argyriadis, P. Passon, T. Camp, R. Cutts. Assessment of bottom-mounted support structure types with conventional design stiffness and installation techniques for typical deep water sites, Deliverable D4.2.1 (WP4: Offshore foundations and support structures), Project UpWind EU Contract No.: 019945 (SES6) “Integrated Wind Turbine Design”, http://www.upwind.eu.

Wang, D., Atlar, M., Sampson, R. (2007). An experimental investigation on cavitation, noise, and slipstream characteristics of ocean stream turbines, *Proc. IMechE Vol. 221 Part A: J. Power and Energy*, 221, 219-231.

Wayman, E.N., Sclavounos, P. D., Butterfield, S., Jason, J., Musial, W. (2006). Coupled Dynamic Modelling of Floating Wind Turbine Systems. *Offshore Technology Conference,* OTC 18287.

Whelan, J., Thomson, M., Graham, J.M.R., and Peir´o, J. (2007). Modelling of free surface proximity and wave induced velocities around a horizontal axis tidal stream turbine, *Proceedings of the 7th European Wave and Tidal Energy Conference*, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Whittaker, T., Collier, D., Folley, M., Osterried, M., Henry, A., Crowley, M. (2007). The development of Oyster – A shallow water surging wave energy converter. Proceedings of the 7th European Wave and Tidal Energy Conference, EWTEC 2007, 11-14 Sep., Porto, Portugal.

Wind Service Holland (2008). http://home.planet.nl/~windsh/offshore.html.

Yago, K. (2008). A Basic Study on Floating Wind Power System for Purpose of Alternative Fuel Production. *Bulletin of Japan Wind Energy Association*, 84, 10-17.