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# Investigating the concept of a novel flexible fabric wave energy device

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## Abstract

This literature review comprises one part of a *project report* which presented the findings of an initial investigation into the concept and performance of a 1:50 scale model novel flexible fabric wave energy device subjected to static tank tests and assessing the model characteristics under load. The topic of wave energy extraction was critically reviewed in terms of the ocean resource and available wave power before wave energy converters were discussed with respect to developmental stages, performance assessment and methods of comparison. The terminology surrounding device capture width was examined and the inconsistent usage of the terms capture width and capture length highlighted with a clear distinction between the two terms proposed. The environmental conditions and capabilities of the Wave Hub site were identified before the topic of flexible fabric structures was introduced. The *project report* concluded with the origins of the conical clam flexible fabric wave energy device and presented an overview of the 1:50 scale model manufactured to validate the concept. Construction methods were documented along with static tank test results which demonstrated how the model device performed under varied load.

## Nomenclature

| ***Symbol*** | ***Description*** | ***Unit*** |
|---|---|---|
| $a$ | wave amplitude | m |
| $A_{wp}$ | water plane area | $m^{-2}$ |
| $c$ | wave celerity | $m\ s^{-1}$ |
| $C$ | capture width | m |
| $C_g$ | group celerity | $m\ s^{-1}$ |
| $C_L$ | capture length | m |
| $C_m$ | capture width / mass | $m\ kg^{-1}$ |
| $C_{max}$ | maximum capture width | - |
| $E_d$ | energy density | $N\ m^{-1}$ |
| $f$ | wave frequency | Hz |
| $f_z$ | natural heaving frequency | Hz |
| $Fn$ | Froude number | - |
| $g$ | gravitational acceleration | $m\ s^{-2}$ |
| $h$ | water depth | m |
| $H$ | wave height | m |
| $H_{mo} \approx H_s$ | significant wave height | m |
| $k$ | wave number | - |
| $L = \lambda$ | wave length | m |
| $L_m$ | model length | m |
| $L_p$ | full scale length | m |
| $m$ | mass | kg |
| $m_n$ | nth spectral moment | - |
| $m_w$ | added mass | kg |
| $P$ | wave power or energy flux | $W\ m^{-1}$ |
| $P$ | total mean power absorbed by device | $W\ m^{-1}$ |
| $P_d$ | power density | $W\ m^{-2}$ |
| $P_{out}$ | electrical power output | $W\ m^{-1}$ |
| $P_w$, | wave power per metre wave front | $W\ m^{-1}$ |
| $P_{wf}$ | power per metre wave front | $W\ m^{-1}$ |
| $S$ | wave spectrum | $S$ |
| $T$ | wave period | s |
| $T_e \approx T_{-10}$ | wave energy period | s |
| $T_p$ | wave peak period | s |
| $T_z$ | wave zero crossing period | s |
| $V_m$ | model velocity | $m\ s^{-1}$ |
| $V_p$ | full scale velocity | $m\ s^{-1}$ |
| β | relevant device width | m |
| η | capture width ratio | - |
| $\eta_L$ | capture length ratio | - |
| $\theta_m$ | wave direction | radians |
| $\pi$ | pi | 3.1416 |
| $\rho$ | density sea water | $kg\ m^{-3}$ |
| $\omega_z$ | natural circular heaving frequency | Hz |

**Ocean energy resources**

According to Panicker (1976, cited in Falnes, 2007), the potential global wave power that hits all coasts worldwide is estimated at around 1 TW and if the potential wave energy was sourced from open oceans the global wave power input is estimated to be around 10 TW. Thorpe (1999a) presented a more conservative figure suggesting that the potential worldwide wave power resource is 2 TW while a more recent study by Mørk *et al.* (2010) estimated the global gross resource at around 3.7 TW. It is clear that the ocean has the capacity to generate a considerable contribution toward human power demands.

It is estimated that on an average day, about 1 TWh of wave energy hits the coast of the British Isles which is roughly the equivalent amount of energy as electricity consumed in the UK each day (Cruz, 2008). Duckers (2004) provided a realistic value of 7 – 10 GW as the UK's potential wave power resource while Drew, Plummer and Sahinkaya (2009) placed these figures into context by claiming that with the UK's total grid capacity being 80 GW and peak demand being around 65 GW, up to 15 per cent of the UK demand could be provided by wave power. In the UK, the Atlantic provides the source for the majority of available wave energy which arrives from the west and is greatest in coastal areas of the British Isles not protected by Ireland, such as off the north west coast of Scotland and to the west of Cornwall where the total annual energy resource is estimated to be around 230TWhy$^{-1}$ (Boud, 2012). Boud (2012) characterised the wave energy resource around the UK at four levels: total resource, theoretical resource, technical resource and practical resource. A summary of available resource estimates for offshore and near shore wave farms in the UK is collated in *the project report*. The total resource is described as the total energy crossing over a theoretical offshore border surrounding the British Isles, stretching toward the Continental shelf and encompassing the Rockall Plateau, while the offshore technical resource estimation, based on calculations derived from modelling wave energy device 'farms' around UK waters, provide a value of 95 TWhy$^{-1}$ (Boud, 2012).

According to The UK renewable energy roadmap (DECC, 2011), evidence suggests that the UK can meet current targets aimed at delivering fifteen per cent of the UK's energy consumption from renewable sources by 2020 and places focus on eight technologies with the greatest potential to help meet the 2020 target. Onshore and offshore wind resources are suggested to provide a combined 60 - 90 TWh, biomass electricity and heat is forecast to produce a combined 70 – 120 TWh while marine resources are viewed to produce just 1 TWh as a contribution toward the 234 TWh making up the estimated fifteen per cent target (DECC, 2011). The ocean energy resources available suggest that this contribution toward UK renewable energy consumption by marine power has the potential to exceed current government expectations and could match that offered by wind and biomass in the future. *The project report* contains a breakdown of the 2020 renewable energy targets set out by the Department of Energy & Climate Change in 2011.

**Wave energy resource**

According to Falnes (2007), the energy stored per unit area of real sea surface can be averaged to:

$$E = \frac{1}{16}\rho g H_{mo}^2 \cong \int_o^\infty S(f)df$$

where $\rho$ is the mass density of seawater, *g* is gravity due to acceleration and $H_{mo}$ is the significant wave height for the associated spectral sea state. The integrand *S(f)* describes the wave spectrum and defines how various frequencies contribute to the total wave energy (Falnes, 2007).

The energy density of a regular wave, $E_d$, is described by Boud (2003) as the mean energy flux crossing a vertical plane parallel to a wave's crest while the wave's power density, $P_d$, is the energy per wave period and is determined by dividing the energy density by the wave period (OPT, 2005; UoM, 2005, cited in Muetze and Vining, 2006):

$$E_d = \frac{1}{8}\rho g H^2 = \frac{1}{2}\rho g a^2$$

$$P_d = \frac{E_d}{T} = \frac{1}{8T}\rho g H^2$$

where, *a* is the wave amplitude, *H* the wave height and *T* the wave period.

The wave power, or energy flux, transmitted by a regular wave per unit crest width is obtained by multiplying the wave energy by the group velocity (Cornett, 2008) and is expressed as:

$$P_w = E_d C_g = \frac{1}{8}\rho g H^2 C_g$$

where *Cg* is the group velocity and is defined as:

$$C_g = \frac{1}{2}\left(\frac{1+2kh}{2\sinh(2kh)}\right)\frac{L}{T} = \frac{1}{2}\left(\frac{1+2kh}{2\sinh(2kh)}\right)c$$

and *h* is the water depth, *L* is the wave length, *T* is the wave period, *k* is the wave number and *c* is the wave celerity. The dispersion equation offers a relationship between wave length, depth and period and is expressed as:

$$L = T\sqrt{\frac{g}{k}\tanh(kh)}$$

Lagoun, Benalia and Benbouzid (2010) refer to the wave resource as the power per metre of wave front:

$$P_w = \mathrm{C}_g E_d = \frac{1}{8\pi}\rho g^2 a^2 T$$

and for regular waves in deep water, the wave power can also be expressed in terms of power per metre where *H* is defined as *2a* length (Lagoun, Benalia and Benbouzid, 2010; Cornett, 2008):

$$P_w = \frac{1}{32\pi}\rho g^2 H^2 T$$

While for irregular waves, the wave power per unit width (Cornett, 2008) is approximated to:

$$P_w \approx \frac{1}{16} H_s^2 C_g$$

where the group velocity is a function of the energy period and water depth. For deep water where the water depth is greater than half the wavelength, the approximation can be simplified to:

$$P_w \approx \frac{1}{64\pi}\rho g^2 H_s^2 T_e$$

and is commonly referred to as the expression for deep water energy flux. The energy period is rarely specified by measured sea states and must be estimated when the spectral shape is unknown (Cornett, 2008). It has been shown that depending on the conditions, $T_e$ may be presumed to be equal to $T_p$ or assuming a standard Jonswap spectrum, $T_e$ is equal to 0.9Tp (Cornett, 2008; Dunnett and Wallace, 2009). Values of 1.14 $T_z$ (ABP, 2004, cited in Cornett, 2008) and 1.269 $T_z$ (Diaconu and Rusu, 2013) have for practical purposes been equated to $T_e$.

According to Barstow *et al.* (2011), in deep water, the wave power is computed by:

$$P = 0.49^2 H_{m0}\ T_{-10}$$

where $T_{-10}$ is the mean energy period defined in terms of the wave spectrum.

Of the expressions defined for power and energy associated with sea waves, in terms of wave energy converter performance assessment, the deep water energy flux has been utilised by many (Ricci *et al.*, 2011; Silva, Rusu and Soares, 2013; Tietje *et al.,* 2011 and Foster, Garambois and Ghorbani, 2011) to carry out more detailed evaluation of the potential energy associated to specific locations. The following paragraphs explain how the data can provide a visual representation of the sea state by means of a histogram displaying wave power contour lines over a bivariate scatter diagram of energy period against significant wave height.

*Wave resource characteristics*

Characterising the wave resource at a particular location allows comparison of wave energy devices and aids in the selection of a device which would perform well in those conditions. Carballo and Iglesias (2012) argued that wave resource assessment must be carried out with due diligence; previous studies have considered too few wave conditions and failed to cover a large enough proportion of the total energy available. The complex process should capture data based on a time period of sufficient duration, which for waves should be ten years or more claimed Kofoed *et al.* (2013), although it may prove difficult to obtain. Carballo and Iglesias (2012) also highlighted the high seasonal variability associated with the wave resource and reasoned that for an accurate assessment, seasonal or even monthly variations of the resource should be considered.

The characterisation, or environmental matrix, is commonly used to describe the wave resource and presents a summary of the key parameters describing the conditions at a particular location (Ricci *et al., 2011*). The resulting scatter diagram presents the long term average probability of occurrence of wave height and period combinations and is typically segmented into ‘bins’ often set at half a metre wave height and one second wave period intervals (Kofoed *et al*, 2013). Carballo and Iglesias (2012) pointed out that as the environmental matrix is likely to be used as a performance indicator for a given device or a number of wave energy devices, the resolution of the environmental matrix must be the same as or finer than the

resolution of the WEC power matrix which is explained in further detail in *WEC Performance Assessment*.

According to Ricci *et al.* (2011), wave performance assessment using spectral parameters and theoretical spectral formulae such as Jonswap may be used to estimate wave power output. Stochastic sea states are often identified by larger bandwidths accounting for low frequency swell components and high frequency wind seas which are often of variable direction. Ricci *et al.* (2011) referred to the use of theoretical spectral shapes representing the wave resource and the application of the modified Pierrson-Moskowitz spectrum as a function of peak period and significant wave height due to its suitability to fully developed seas. Tietje *et al*. (2011) support the use of principle spectral parameters which are presented in terms of moments of the spectrum representing incidental wave power arriving at the WEC.

The nth spectral moment is defined as:

$$m_n = \sum_{i=1}^{N} S\, f_i \Delta f_i$$

where $S$ is the wave spectrum and $f_i$ the wave frequency. The significant wave height, $H_{mo}$, can be determined from:

$$H_{mo} = 4.0\ (m_o)^{1/2}$$

The energy period is calculated using:

$$T_e = T_{-10} = \frac{m_{-1}}{m_o}$$

while the energy flux, $P$, is given by:

$$P = \rho g \sum_{i} S\ C_{gi}\ \Delta f_i$$

It has been hypothesised by Ricci *et al.* (2011) among others that as the water depth becomes large and *kh* tends toward infinity, the expression for wave energy flux is reduced to the simplified derivation given in *Wave Energy Resource*.

Carballo and Iglesias (2012) also presented the mean wave direction, $\theta_m$, in terms of spectral shape as:

$$\theta_m = \int_0^{2\pi} \int_0^{\infty} \theta S\ (f, \theta) df\ d\theta$$

**Capture width**

It has been shown by many (Budal and Falnes, 1975; Evans, 1976 and Newman, 1976, cited in Falnes, 1997; Price, Dent and Wallace, 2009; Falcao, 2010) that the maximum energy which may be absorbed by a heaving axisymmetric body is equal to the energy delivered by the incident wave front of width equal to the wavelength divided by two pi. Thus for a heaving axisymmetric body, the maximum capture width, $C_{max}$, a measurement not accounting for losses due to friction and other effects (Falnes, 1997), may be expressed as:

$$C_{max} = \frac{\lambda}{2\pi}$$

Given the power per metre wave length and the power absorbed by a wave energy converter, the capture width, *C*, of a device may be determined which has been defined by Cruz (2008) as the ratio of the total mean power, *P*, absorbed by the body to the mean power per unit crest width, $P_w$, of the incident waves and has a dimension of metres given as a length:

$$C = \frac{P}{P_w}$$

Therefore the power absorbed by a heaving axisymmetric body can be described as:

$$\mathrm{P} = CP_w$$

and shows that a device captures the amount $CP_w$ from the wave front (Cruz, 2008).

Babarit and Hals (2011) suggest that efficiency is sometimes regarded as the ratio of the absorbed power to the available power resource, a matter complicated by factors depending on device shape, mode and size. The capture width ratio, $\eta$, is thus used to define the ratio between absorbed power and the available wave power per meter wave front multiplied by a relevant device dimension, $\beta$ , in metres:

$$\eta = \frac{P}{P_w \beta}$$

The dimension $\beta$ is dependent on the working principles of the device and is often chosen as the device width (Babarit and Hals, 2011) with the exception of wave energy converters such as terminators whose length is more dominant than breadth. The annual capture width ratios of a number of devices have been collated by Babarit and Hals who have estimated that typically, oscillating water column devices have a capture width ratio of around 33%, heaving buoys around 10–30% (larger buoys gave a greater percentage), pitching devices 20-40% (seabed mounted devices averaged 40%) and overtopping devices averaged around 15%. *The project report* presents the findings of Babarit and Hals comparison study of WEC's in terms of the capture width ratio.

The definition of capture width has been suggested by many as a useful parameter for comparing wave energy converters and when combined with device mass offers a sensible approach to device comparison due to cost being roughly proportional to device mass (Farley, 2008). Hence $C_m$ may be expressed in terms of meters per tonne where *m* is the device mass:

$$C_m = \frac{\lambda}{2\pi m}$$

Price, Dent and Wallace (2009) have extended the theory on capture width and have introduced a revised formulation assuming the use of discrete rather than continuous Fourier transform series and expressing polychromatic capture as a function of two parameters describing the monochromatic capture width and the sea state in terms of the recently conceived spectral power fraction.

The term capture length has been described by the European Marine Energy Centre (EMEC) as the measure of device performance in terms of the ratio of electrical power output of a WEC to the corresponding wave power (Pitt, 2009):

$$C_L = \frac{P_{out}}{P_w}$$

The capture length has a unit of metres and EMEC's WEC system performance guide states that it should not imply any value of efficiency nor should it be related to the physical properties of the WEC. Calculating the capture length has been utilised as a method for producing WEC performance indicators as there is little variation associated with the significant wave height and the energy period (Tietje, 2009).

Tietje *et al.* (2011) refer to the capture width and the capture length as the same property which for a given sea state is defined as the ratio of device power output, $P_{out}$, to available wave power or wave energy flux:

$$C_L = \frac{P_{out}}{P_w}$$

It is evident that there are some inconsistencies in the approach taken by authors on the terminology surrounding capture width. For the purposes of this report and any further work, capture width shall be defined as the ratio between power absorbed and available wave power (mean power per metre wave length, $P_w$) while capture length is the ratio between device output and available power.

According to Kofoed *et al.* (2013), the capture width ratio (referring to efficiency) is related to the ratio between power output and available power rather than the ratio between power absorbed and available power suggested by Babarit and Hals (2011). Thus it may again be useful to refer to the term regarding power output as the capture length ratio, $\eta_L$:

$$\eta_L = \frac{P_{out}}{P_w \beta}$$

## Wave Energy Converters

### *WEC categories*

According to Falcao (2010), several methods have been proposed to classify wave energy converters according to location, working principle and size. Early wave device development concentrated mainly on floating devices according to Cruz (2008) which resulted in three classifications of point absorbers, terminators and attenuators. Thorpe (1999b) presented a number of wave energy devices according to deployment and being shoreline, near shore or offshore categories while Muetze and Vining (2006) have grouped devices in terms of their working principle and being either of an oscillating water column, overtopping or buoy type wave energy converter. It has been suggested that wave energy converters can also be categorised by their power take off system (Lagoun, Benalia and Benbouzid, 2010) while McCormick (2007) utilised a classification system based on energy conversion techniques including: heaving and pitching bodies, cavity resonators, pressure devices, surging wave converters, particle motion converters and advanced techniques. Falcao (2010) offered a more detailed breakdown of working principle

classification and categorised a number of devices that have reached either the prototype stage or were the subject of extensive development which are presented in *the project report*.

According To Location

Shoreline devices have a number of advantages and disadvantages over near shore and offshore locations. Located on the coastline, utility networks are easily established and maintained (Drew, Plummer and Sahinkaya, 2009) while device installation and maintenance is more easily accessed and less costly (Clement *et al.*, 2002; Thorpe, 1999b). Drew, Plummer and Sahinkaya (2009) suggest that as waves reach the shore their loss of energy reduces the potential of device damage in extreme weather conditions although this loss of available energy may be compensated by high energy concentration hotspots (Clement *et al.*, 2002; Thorpe, 1999b). Shoreline device deployment also faces limitations due to shoreline geology and coastal preservation (Thorpe, 1999b).

Near shore devices are defined by Drew, Plummer and Sahinkaya (2009) as those that are located in relatively shallow water although the term shallow water holds some ambiguity. Duckers (2004) suggested that shallow water could be considered as less than one quarter of the wave length while others have proposed that near shore devices are those installed in moderate water depths of around twenty metres and less (Clement *et al.,* 2002; Thorpe, 1999b).

Offshore devices are able to harvest energy from more powerful waves in deep water, described by greater than forty metres by many (Duckers, 2004; Clement *et al.*, 2002; Thorpe, 1999b) although some ambiguity also arises from the term deep water with some claiming that tens of metres constitutes deep water (Boud and Callaghan, 2006, cited in Drew, Plummer and Sahinkaya, 2009) and others suggesting that deep water is of a depth exceeding one-third of the wavelength (Falnes, 2007). Drew, Plummer and Sahinkaya, (2009) described how offshore devices are more difficult to construct and maintain due to greater wave heights in deep water and the necessity for the design to withstand more extreme conditions occurring offshore leading to greater construction costs.

Thorpe (1999b) provides a thorough description of a number of devices related to location including the Limpet OWC (shore line), the Osprey OWC (near shore) and Salter's Duck (offshore) and offered a measure of commercial viability by predicting the cost of electricity produced before discounting over the lifetime of the device.

According To Working Principle

Point absorbers are devices that are usually axisymmetric about the vertical axis and small in relation to the incident wavelength (Cruz, 2008; Drew, Plummer and Sahinkaya, 2009). Either being a floating structure or submerged body relying on pressure differentials, the direction of the incident waves are not usually important (Drew, Plummer and Sahinkaya, 2009), while floating point absorbers can possess a large capture width and have the capacity of absorbing wave front energy many times greater than the physical dimensions of the device (Cruz, 2008). Heaving body point absorbers are examined in more detail in *Heaving Body WECs*.

Terminators are devices which intercept waves and have a principle axis perpendicular to the wave direction with beams much greater than length (Cruz, 2008; Drew, Plummer and Sahinkaya, 2009). Capturing or reflecting wave power,

terminators are typically found on the shoreline or near shore although floating terminators have been designed as offshore devices (BOEM, 2013).

Attenuators, like terminators, have one principal horizontal axis relative to the incident wave but are aligned to the wave direction with their breadth much smaller than their length (Cruz, 2008) while energy is produced by selectively constraining movements along its length (Lagoun, Benalia and Benbouzid, 2010).

The European Marine Energy Centre (EMEC) have identified eight main types of wave energy converter as attenuators, point absorbers, oscillating wave surge converters, oscillating water columns, overtopping devices, submerged pressure differential devices, rotating mass devices and other devices with designs differing to the well-established categories given (EMEC, 2013b). A list of 167 known wave energy developers are listed (EMEC, 2013a) indicating the number of WEC's under development. Some concepts which have reached the full scale stage are described in detail by Cruz (2008) and include Pelamis, Wave Dragon and Archimedes Wave Swing (AWS).

*Comparable WEC's*

There are a number of methods available for comparing wave energy converters. Available data may be obtained from manufactures providing WEC specific characteristics such as the capture width ratio or the average annual power production in the form of a power matrix.

In 2002, Nielson's Bolgekraftprogram produced results of energy absorption and cost estimate comparison studies of fifteen different WEC's obtained through tank test experiments. WEC efficiencies were given in terms of capture width ratio and the devices ranged from 4% to 34%. The devices subjected to examination included Swan DK3, Wave Dragon, Wave Plunger, Poseidon, Pico Plant, Pelamis and Mighty Whale. A summary of Nielson's work, providing data for device comparison, is presented in *the project report*. More recently, Babarit and Hals (2011) compiled further research on the capture width ratio of more than twenty devices including Seadog, Aquabuoy, Wavebob, Oyster, Langlee and Searev. A summary of the capture width ratio of WEC's presented by Babarit and Hals is also given in *the project report*.

There have been numerous studies either comparing a number of devices at a given location (Dunnett and Wallace, 2008; Diaconu and Rusu, 2013; Silva, Rusu and Soares, 2012) or providing methodologies to determine the performance of a WEC at a given location (Carballo and Iglesias, 2012; Babarit and Hals, 2011; Tietje *et al.,* 2011; Burger and Gardner, 2005). A number of WEC power matrices have been obtained from published articles and include Aquabuoy, Wave Dragon, Pelamis, Seaweave Slot Cone Generator, Oyster, AWS, Langlee, Oceantec, OE Buoy, Pontoon, Seabased AB and Wavebob. *The project report* presents the WEC power matrices compiled from literature.

*Heaving body WEC's*

According to McCormick (2007), in monochromatic waves a floating heaving body will have a natural heaving period and the corresponding natural frequency for a given WEC should be designed to resonate with either the highest energy waves in a wind sea or a predominant swell. The natural heaving frequency, $f_z$, of a floating heaving body is given by McCormick (1973, cited in McCormick, 2007) as:

$$f_z = \frac{1}{t_z} = \frac{\omega_z}{2\pi} = \frac{1}{2\pi} * (\frac{\rho g A_{wp}}{m + m_w})^{1/2}$$

where $t_z$ is the natural heaving period, $\omega_z$ is the natural circular heaving frequency, $A_{wp}$ is the waterplane area of the float, $m$ is the mass of the heaving device and $m_w$ is the added mass (stated as the mass of water excited by the heaving motion). McCormick (2007) goes on to stress the significance of the frequency expression and argues that when a body with natural heaving encounters waves of the same period, a maximum motion is expected whose amplitude will depend on the damping of the system.

Falnes (1997) supports the theory of obtaining maximum energy from waves through optimum oscillation design of wave energy converters and notes that optimum vertical oscillations of a given device are proportional to the amplitude of the incident wave. Falnes (1997) suggests that by matching the wave frequency to the natural frequency of the device, the oscillatory velocity of the system will also be in phase with the wave's exciting force acting on the device and highlights that optimum conditions are approximately satisfied for wave frequencies within a resonance bandwidth of the system. Falnes (1997) states that device bandwidths are proportional to device dimension, and that larger devices have broad bandwidths while physically smaller devices have a more narrow frequency bandwidth. It is for this reason that phase control is important when trying to match smaller sized devices to particular sea states in order to obtain optimum conditions. Phase control by latching is one method highlighted by Falnes (1997).

Falcao (2010) provides an overview of the additional issues resulting from the presence of power take off systems introduced into the study of hydrodynamics of floating WEC's. Optimum conditions are provided for a linear damping coefficient and angular frequency. According to Falcao (2010), the ideal resonance condition for a body with a symmetrical vertical axis yields an optimum radius of 0.262$T$ where $T$ is the wave period. In the Northern Atlantic where the wave period may be ten seconds, an optimum device radius would be 26.2 metres.

*WEC performance assessment*

An adaptable specification for standardising performance assessment of wave energy converters, developed to evaluate WEC's ready for commercial deployment and provide electrical power, was initiated to provide a uniform method to assess WEC performance in the form of a power matrix (Tietje *et al.*, 2011)

Typically, as shown in *Wave resource characteristics*, sea states can be characterised by two parameters, $Hs$ and $T_e$ thus it is beneficial if the power output of a WEC is represented as a two dimensional function of $Hs$ and $T_e$. The energy output is then calculated by combining the two matrices for the specific location, the first being the probability of occurrence of sea states known as the environmental matrix and the second describing the energy produced by the WEC in a certain sea state (Burger and Gardner, 2005). According to Dunnett and Wallace (2009), WEC performance data in terms of $H_s$ is easily obtained however some WEC manufacturers provide measures of wave period such as $T_p$, the peak period, $T_z$, the zero crossing period and $T_{pow}$, the power period, which is the period of a sinusoidal wave with the same incident power of the seas state, all of whose relationships with the energy period depends on the spectral distribution of the component waves.

For each combination of values representing wave height and wave period, the power matrix produces an average power output value, although the matrix may say little about the sensitivity of the device to changes in sea state characteristics (Smith and Taylor, 2007). For this reason, Smith and Taylor's WEC performance protocol commissioned by the Department of Trade and Industry (DTI) advises on the possible use of additional performance matrices to further understand the performance of the device. Five examples of performance matrices are given as: mean power, maximum power, minimum power, standard deviation of power values and the total number of records. Smith and Taylor (2007) state that for devices insensitive to wave direction and spectral shape, the mean, maximum and minimum values will produce predicable behaviour and a standard power matrix would describe the relationship between seas state and power. On the other hand, devices with relatively narrow bandwidths would best be described using a full set of performance matrices.

**WEC development**

Clement *et al.* (2002) compiled extensive research on wave energy conversion and reviewed and described current activities during the nineteen nineties in Europe. Denmark, Ireland, Norway, Portugal, Sweden and the UK are all engaged in wave energy utilisation and received governmental support which has led to much research and development in wave power conversion (Clement *et al.,* 2002). Drew, Plummer and Sahinkaya (2009) produced an overview of UK based companies currently developing wave power devices as commercial operations which is listed in *the project report*.

The Sustainable Power Generation and Supply programme, SuperGen, founded by The Engineering and Physical Sciences Research Council conducts research leading to improvements in the sustainability of the UK's power generation and supply and aims to establish a platform for the development of new and improved devices for sustainable power generation. In 2003, Phase 1 of the research initiative brought together a collection of research staff from UK universities to undertake long term research objectives to increase knowledge and understanding of energy extraction from the sea, to reduce risk to stakeholders and to enable progression of marine technology in future energy portfolios (SuperGen, 2011). Phase 2 commenced in 2007 seeing further affiliations made between UK researchers and objectives undertaken included increasing knowledge and understanding of device interactions in laboratory model scale testing and full scale open sea testing, to increase capacities to conduct further research addressing new challenges and to internationalise activities, perception and influence (SuperGen, 2011). 2011 saw funding secured for a further five years of research and the formation of the UK Centre for Marine Energy Research whose aim is to meet the challenges of accelerating deployment and whose objectives are to conduct applied research and ensure growth in generating capacity, to expand and operate with industry partners and international collaborators and to provide training and knowledge transfer to build intellectual capacity for the sector (SuperGen, 2011).

*WEC developmental phases*

Funded by the European Commission, the EquiMar project was a collaborative research and development project involving a consortium of 23 partners running for three years from 2008 to 2011 whose aims were to deliver a suite of protocols for the evaluation of marine energy converters. EquiMar have assessed devices using a

suite of protocols covering site selection, device engineering design, design scaling, array deployment, environmental impacts in terms of biological and coastal processes and economic issues. The results from the EquiMar project intended to establish a sound base for future marine energy standards (EquiMar, 2013).

The Hydraulics and Maritime Research Centre (HMRC) development and evaluation protocol published in 2003 for the advancement of wave energy devices focused on the evolution of wave energy converters rather than generic aspects of wave energy extraction. The HMRC protocol is separated into five distinct phases, each determined by the type of scaled physical or mathematical model required. Phase 1 is the initial conceptual model trial period and phase 5 the full scale demonstration unit. Each of the developmental stages are outlined in *the project report* and are regarded as the minimum standard required to effectively develop a product from the initial conception to market and although divisions between phases may not be entirely clear where stages may overlap, the phase stages should never fully merge or combine (HMRC, 2003).

*WEC testing facilities*

Amongst the EquiMar protocols is found D4.3, a Test Sites catalogue designed to provide data on the full scale test sites set up around Europe to allow for wave and tidal energy device testing and to support wave energy device development progression (EquiMar, 2013). The catalogue aims to list the infrastructure and support services sites should provide to fully support developers, to describe existing and proposed wave and tidal energy test sites and to overview development schedules and the role in which site selection plays in device development. The test sites listed all house the following requirements in order to offer full developmental support: met-ocean conditions, grid connection, wave, meteorological and current measurements, proximity to support facilities, licensing and permits and onshore monitoring facilities (O'Conner and Holmes, 2011). *The project report* presents the range of full scale, nursery and independent test sites listed by EquiMar in Europe and the wave energy resource associated with each site.

**Wave Hub site**

The Wave Hub full scale wave energy converter test site is located around ten miles north of Hayle, Cornwall, and was installed in 2010 to provide test facilities for different technologies with grid connections allowing developers to lease sea area and test prototype devices for a period of five years and more (O'Conner & Holmes, 2011). Operating at 11 kV, the site allows developers to generate around 5 MW each although this figure could double if the site upgrades the total capacity to 33 kV (EquiMar, 2011). Nielson and Pontes (2010, cited in O'Conner & Holmes, 2011) calculated the average wave energy resource at the Wave Hub site to be 17 kW/m while Baldock *et al.,* (2011, cited in O'Conner & Holmes, 2011) estimated the annual average wave energy resource to be between 16.9 and 18.5 kW/m. *The project report* presents the statistics summary for the Wave Hub site and displays the design parameters for peak period and significant wave height.

Phillips *et al.* (2008) produced a long term wave resource prediction at the Wave Hub site following the use of measured and modelled wave data in the context of a Measure-Correlate-Predict (MPC) analysis with a value of 16.8 kW/m which is comparable to the figure estimated by Pitt (2006) of 17.7 kW/m. An environmental matrix describing the predicted wave climate at the Wave Hub site was produced by Phillips *et al.* (2008) and is presented in *the project report*. The available average

resource of 17 kW/m corresponds to a significant wave height of 1.5 m and wave energy period of 7 s. Annual average power densities for the site are also provided by Phillips *et al.* (2008) showing a range between 14 kW/m and 34 kW/m over a six year period along with a seasonal variation of the key parameters, $H_s$, $T_e$ and power density presented as the standard deviation to the mean. *The project report* presents the annual average power densities found between 2000 and 2006 along with the inter-annual variation of parameters for the site.

According to Babarit and Hals (2011), for a typical site whose resource is 20-30 kW/m, the upper limit of mean power absorption in regular waves is about 1 MW for a heaving WEC. Further studies on power absorption measures by Babarit *et al.* (2011) suggest that for a typical European site where the wave resource is around 25kW/m, a heaving buoy was shown to absorb around 3 kW, corresponding to a capture width ratio of around 4% and a value in the region of ten times less than that of a floating OWC due to the smaller dimensions of a heaving point absorber. Heaving bodies and OWC's were shown by Babarit *et al.* (2011) to absorb more power as the available wave power increased unlike pitching devices. SWERDA (2006) describe the design wave for survivability testing at the Wave Hub site with a significant wave height of 14.4 metres and peak period of 14.1 seconds indicating a device located at the site would be best equipped with both a wide frequency band and effective survivability measures.

**Flexible fabric structures**

During the 1980's, the Circular Sea Clam wave energy device was developed which consisted of a long floating spine supporting six air bags producing an air flow through a Wells turbine (Bellamy, 1986). Today, there are a number of wave energy devices utilizing flexible fabrics as an integral part of working principle. The free floating clam device added a new concept of a variable body volume and is discussed in *The Conical Clam* in the *project report*. The AWS III device incorporates an array of interconnected compressible cells which produce energy by moving air through a turbine between the cells. The device has a diaphragm around the outer edge which moves with wave action relative to the cell causing pressure differentials and air movement (AWS Ocean Energy, 2013).

The Anaconda is described as a closed rubber tube filled with water, anchored to the seabed with its head facing the incidental wave direction and experiencing pressure variations due to sea waves generating bulge waves within the tube (Chaplain *et al.,* 2007). Development of the Anaconda has been relatively well documented and papers have been published on physical model testing and the hydrodynamic performance of the device. The Fabriconda is an attenuating wave energy device based on the Anaconda and has ten fabric tubes forming a large central tube pressurised with water. According to Hann, Chaplain and Farley (2011), pressure changes occur as the waves pass over the device and bulges propagate along the tube. Experimental procedures were documented and results indicated a good correlation between measured and theoretical values.

Pimm's 2011 work on flexible fabric strictures was focused on the analysis of energy bags used for subsea compressed air energy storage and their optimal design. Three analysis methods were employed to investigate the deformed shape experienced by the bags under pressure and cutting patterns for lobed balloons analysed. According to Pimm (2011), it is desirable for energy bags to behave as balloons in their capacity for total flexibility so that volume changes depending on the

energy stored in the air and the internal pressure remains close to the hydrostatic pressure in the surrounding water. A variation of the energy bag evolution was a pumpkin shaped balloon consisting of two flat, circular pieces of material joined at the edges. The flexible membranes transmit in-plane tension loading and under uniaxial compression while wrinkles appear perpendicular to the direction of compression (Pimm, 2011). Pimm refers to this action as uniaxial wrinkling as under biaxial compression the membrane loses tension and slack (or biaxial) wrinkling occurs. Models of the energy bag were manufactured from two circular pieces of fabric welded at the edges with tendons running through guides attached to the outer surface of the fabric. Pimm (2011) explains how a natural shape must form due to the width reducing as the bag inflates while the tendons are shortened relative to the fabric resulting in a transfer of meridonial stress from the fabric to the tendons while the fabric carries only circumferential stress. These models are very simple in concept and require two pieces of fabric and one weld for each bag, greatly reducing the complexities rising from balloon lobe cutting patterns.

The *project report* goes on to describe how Pimm's techniques were applied to Farley's floating clam wave energy conversion concepts (Farley, 2011) before documenting construction methods for a 1:50 scale model flexible fabric wave energy device, preliminary experimental methods and static test results.

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