A database of capture width ratio of wave energy converters

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Abstract

The aim of this study is to establish a database for the hydrodynamic performance of Wave Energy Converters (WECs). The method relies on the collection and analysis of data available in the literature. The availability and presentation of these data vary greatly between sources. Thus, extrapolations have been made in order to derive an annual average for the capture width ratio (CWR) of the different technologies. These CWR are synthesised in a table alongside information regarding dimension, wave resource and operational principle of the technologies. It is observed that CWR is correlated to operational principle and dimension. Statistical methods are used to derive relationships between CWR and dimension for the different WEC operational principles.

Keywords: Wave energy converter, capture width ratio, hydrodynamic efficiency, database.

1. Introduction

Since the early 1980s, hundreds of Wave Energy Converters (WECs) have been studied and developed. Full-scale prototypes have been tested, and technology review papers have been published (see for example [1], [2], [3], [4], [5], [6], [7], [8]). These papers usually discuss the technologies, their classifications and technical aspects (e.g. the Power Take-off (PTO) system). They do not discuss power performance of the different wave energy technologies.

Information on power performance can be found in the literature, however in general, the information provided by any given paper is limited to the one technology being investigated. A few studies have compared power performance between different technologies, but they cover a limited number of devices [9], [10], [11], [12].

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Thus, the aim of this paper is to create an extensive database for the hydrodynamic performance of WECs by reviewing power performance results available in the public literature. In this paper, the approach elaborates and extends on the work by [13]. Power performance is quantified in terms of capture width ratio (CWR), which is reported for each device in tables 7, 8 and 9. To identify trends, the results were classified according to WEC operational principle. A relationship between dimension and CWR was identified and discussed in the last part of this paper.

It must be acknowledged that making an objective comparison of CWR across WEC technologies is not an easy task. In this work, it has been necessary to make assumptions and approximations in order to address issues related to discrepancies in the collected data. These are discussed in section 2 and section 4, and are believed to be reasonable. However, it is nevertheless possible that they may influence the final results in section 4. Since all assumptions and approximations made have been described in detail in this paper, the extent of this influence may be assessed in future work.

2. Methods

The sources for the present work are references [9] to [11] and [14] to [45], which present performance results for various WECs. The performance measure used and the way in which results are presented vary greatly from one source to another. Thus, for the purpose of comparison, it was necessary to select a common performance measure, namely annual average of CWR. Note that CWR may also be referred to in the literature as ”‘non-dimensional performance”’ [12].

2.1. CWR

Capture width (CW) was first introduced in 1975 by [46]. It is defined as the ratio of absorbed wave power P (in kW) to the wave resource J (in kW/m):

$$CW = \frac{P}{J} \tag{1}$$

The unit of capture width is a length in meters. It may be interpreted as the width of wave crest that has been completely captured and absorbed by the WEC.

More than capture width, it is hydrodynamic efficiency that best reflects the hydrodynamic performance of a WEC. A measure of the hydrodynamic efficiency is the CWR, obtained by dividing the capture width by a characteristic dimension B of the WEC - often the device width. CWR, denoted by η_1, reflects the fraction of wave power flowing through the device that is absorbed by the device:

$$\eta_1 = \frac{CW}{B} = \frac{P}{JB} \quad (2)$$

Selection of a relevant characteristic dimension for B is critical in order to make CWR comparable between different wave energy devices. This is discussed further in section 2.4.

It is important to note that CWR relates to hydrodynamic power performance (energy absorption) and not economical performance (cost of energy). Efficiency in the PTO system and the power conversion chain, as well as fabrication and operation costs, may be such that the most efficient device hydrodynamically speaking could be the least efficient device from the perspective of cost of energy.

2.2. Harmonization of power performance results

Only a few of the sources present data for the annual average of capture width and wave resource J. In other cases, it is necessary to extrapolate from available results to estimate CWR. The methodology is illustrated in figure 1 and discussed in the following.

In some of the sources, power matrices are provided. In these cases, estimates of annual average capture width at different locations are obtained by first multiplying scatter diagrams with power matrices and then summing the power contributions from each sea state. Scatter diagrams shown in [11] were used. Linear interpolation is when the bins of the power matrix and the scatter diagram do not match.

In other sources, information about capture width or power absorption is provided for only a limited number of sea states. In these cases, it is necessary to estimate the power matrices as follows. First, it was assumed that power absorption is zero for sea states with peak period less than 3 seconds or greater than 20 seconds. Then, linear interpolation was used to obtain power absorption as a function of the peak period. Finally, the power matrix was fully populated by scaling power absorption with the square of

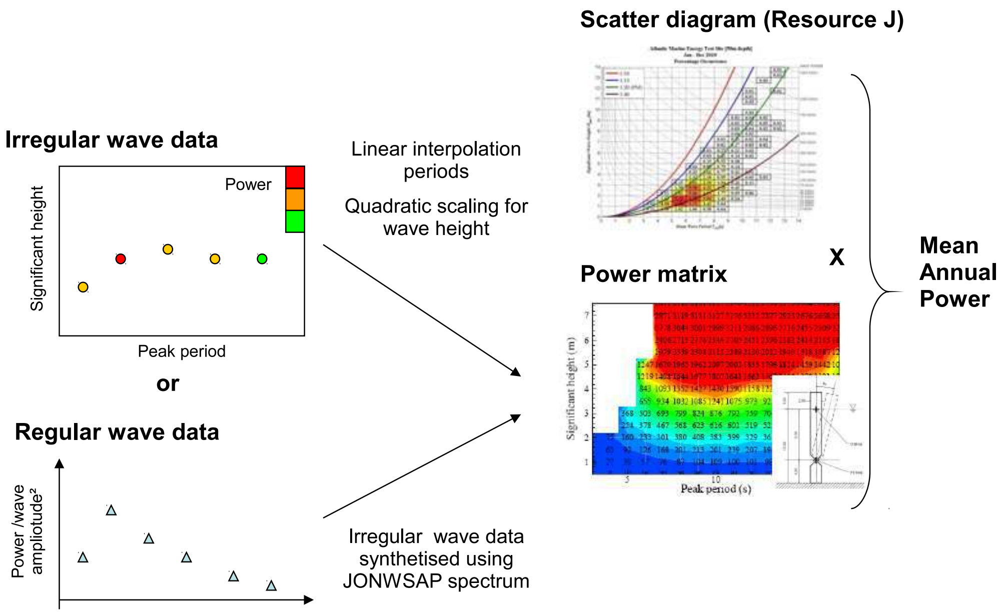

Figure 1: Outline of the methodology used for the harmonization of power performance results.

significant wave height. Once the power matrix was derived, annual average capture width was calculated using the methodology explained in the previous paragraph.

Still other sources provide information on performance only in regular waves. In these cases, power matrices were generated, again assuming linearity. Power absorption in regular waves was obtained by integrating over frequency the product of Jonswap spectrum with the power absorption in regular waves. Once the power matrix was determined, annual average of capture width was determined as explained previously.

Finally, some sources provide data on power absorption with and without advanced control (e.g. latching control, in the case of source [22]). Only power absorption with passive control was retained in the database. This was essentially for the sake of consistency, but also because many practical challenges remain to be solved before advanced control is feasible [48], [47], [49].

2.3. *Classification of technologies*

WEC technologies may be classified by: their dimension and arrangement with respect to the main wave direction; their distance to shore; or their operational principle. One of the most representative classifications on the basis of operational principle was proposed by Falcão [4]. In this classification, devices are grouped into three main categories: oscillating water columns (OWCs), overtopping devices or oscillating bodies (referred to as wave-activated bodies in [4]). Since oscillating bodies covers a broad range of devices, this category was divided further into floating or bottom fixed devices (the latter referred to as "submerged" in [4]); and Oscillating Wave Surge Converters (referred to as "essentially rotation" in [4]) or heaving devices (referred to as "essentially translation (heave)" in [4]). In this work, we follow the same classification, except that no distinction is made between floating and bottom-fixed heaving devices. Thus, oscillating bodies are classified as either heaving devices (devices moving essentially in heave), fixed OWSCs (OWSCs attached to a fixed reference), or OWSCs attached to a floating reference.

For oscillating bodies, it is believed that this distinction between heaving and surging devices has to be made because the direction of motion is an important parameter for hydrodynamic performance. Indeed, a well-known remarkable result in wave energy conversion is that, under certain assumptions, CWR relates only to the wavelength and the degree of freedom of the device [50], and not to its physical dimensions. Assuming (i) that linear potential flow theory is applicable and (ii) an axisymmetrical WEC (iii) with optimal reactive control, the theoretical maximum for the capture width is:

$$CW_{max} = \epsilon \frac{\lambda}{2\pi} \tag{3}$$

where λ is the wavelength and ϵ is a coefficient dependent on the pattern of the radiated wave far field, and thus on the degree of freedom. If the system is moving in heave (heaving buoy), the far field component of the radiated waves has a circular pattern (left figure in figure 2) and the coefficient ϵ is equal to 1. If the system is moving in surge and/or pitch, the wave pattern is antisymmetric (right figure in figure 2) and the coefficient ϵ is 2. The theoretical maximum for wave absorption of an axisymmetric WEC moving in surge or pitch is twice that of for the same WEC moving in heave.

These theoretical results highlight the importance of the radiated wave pattern on the hydrodynamic performance of a WEC; hence, a WEC classi-

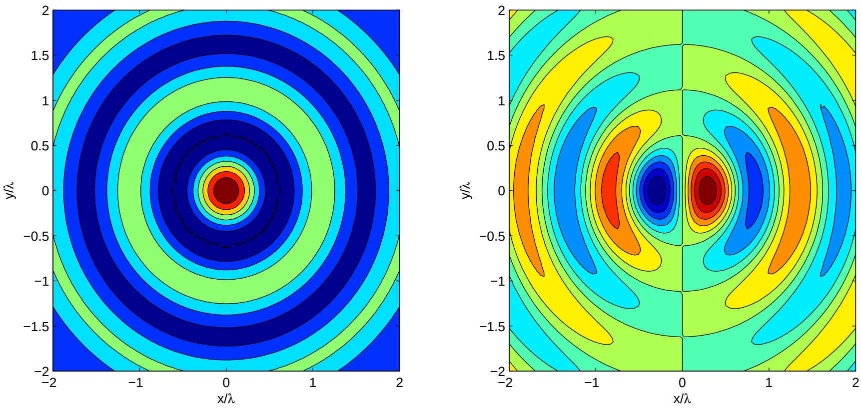

Figure 2: Far field pattern of the radiated wave for an axisymmetric device moving in heave (left graph) and in surge (right figure).

fication should take into account the WEC's far field radiated wave pattern. As this pattern is essentially related to the direction of motion, it represents a distinction between heaving devices and OWSCs. The latter have been further subdivided into devices attached to a fixed reference or a floating reference. Indeed, performance of floating OWSCs is considerably less than devices held to a fixed reference because the whole platform has a tendency to move as a rigid body instead of developing relative motion.

Figure 3 shows the archetypal device for each category. It must be acknowledged that in practice, devices may differ significantly from the archetype. In some examples, the operational principle may be the only relationship between the device and the archetype. Thus, it was decided to sub-divide each category into those devices that are close realizations of the archetype, and those devices that are related to the category essentially by the operational principle. This distinction leaves us with the following ten categories: OWCs, variants of OWCs, overtopping devices, variants of overtopping devices, heaving devices, variants of heaving devices, fixed OWSCs, variants of fixed OWSCs floating OWSCs and variants of floating OWSCs.

Note that, in this study, articulated devices such as the Pelamis or the DEXA are classified as variants of heaving devices. This is because: (i) to first order, the motion of the center of the floats is vertical, and (ii) from the hydrodynamical perspective, they can be approximated as a series of heaving buoys [51].

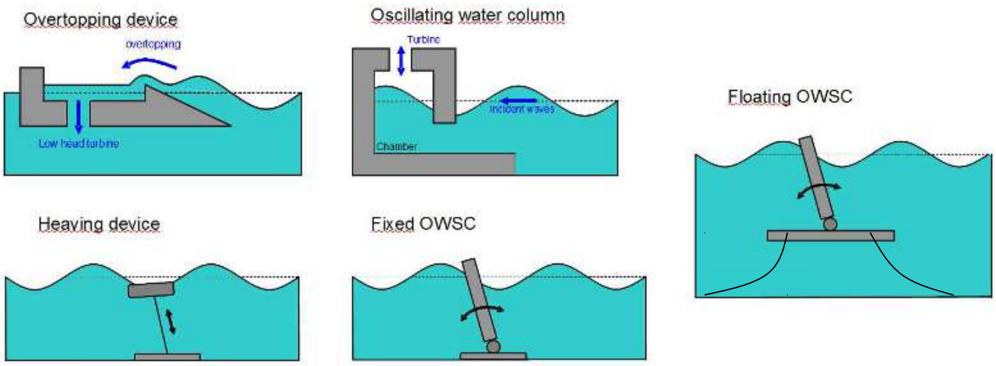

Figure 3: Illustration of the archetypal wave energy device for each category

Most WECs proposed so far fall into one of these ten categories. However, there are exceptions, such as wave turbines [52], [53] or flexible devices [54], [55]. These have not been considered in this study because the available information is much more limited than for the other ten categories.

2.4. Selection of the characteristic dimension

For all except heaving devices, active width was used as the characteristic dimension, B, for calculating the CWR. The definition of [12] for the active width was followed, which is based on the idea that "(...) width of all the components actively in the primary absorption process of the energy from the waves should be included". Thus, in the case of a device composed of a platform with many WECs attached to it, the performance was normalised by the number of WECs on the platform and the active width was the width of each individual WEC. In the case of devices with reflectors or a wave concentration mechanism, the active width includes the reflectors. In the case of devices inclined relative to the incoming waves, the real (not projected) width was taken into account.

For heaving devices, the characteristic diameter is obtained according to:

$$B = \sqrt{\frac{4A_W}{\pi}} \quad (4)$$

where A_W is the maximum horizontal cross-sectional area of the device, assumed to be the main driver for the ability of a heaving device to generate waves (and thus absorb waves [1]) . Note that for vertical cylinders or floating hemispheres, A_W is simply equal to the diameter.

2.5. Additional information added to the database

The methodology used to derive the power performance results is important information to collect and retain in the database. Depending on the sources, numerical or experimental modeling has been used. For experimental modeling, the scale varies from small-scale to full-scale prototype. This information was included in the database.

Performance results may have been obtained by technology developers or third parties. This information was also collected and retained in the database, as occasionally performance results from technology developers may be suspected of unreliability due to conflicting interests.

3. Review of power performance results

3.1. List and discussion of sources

In this section, the sources used to compile the database are presented and discussed.

3.1.1. Oscillating water columns

Pictures of the OWC technologies discussed in this section are shown in figure 4.

- Reference [14] reports experimental performance results for the NEL-OWC, which is a floating terminator device composed of several OWC modules mounted on a spine. The device was tested at large scale in the Solent with three, five and eight modules, each module having width of 1.5 m. Figure 11 of the paper presents CWR measured during the sea trials as a function of the energy period. The large spread of the sea trial results can be attributed to the varying properties of the waves. The eight module configuration gave best performance so was selected by us for estimation of the mean annual CWR. Assuming that the scale of the model was 1/20, we estimated mean annual CWR to be respectively 22, 27, 29, 23 % for sites with wave resource 16, 23, 27, 37 kW/m.

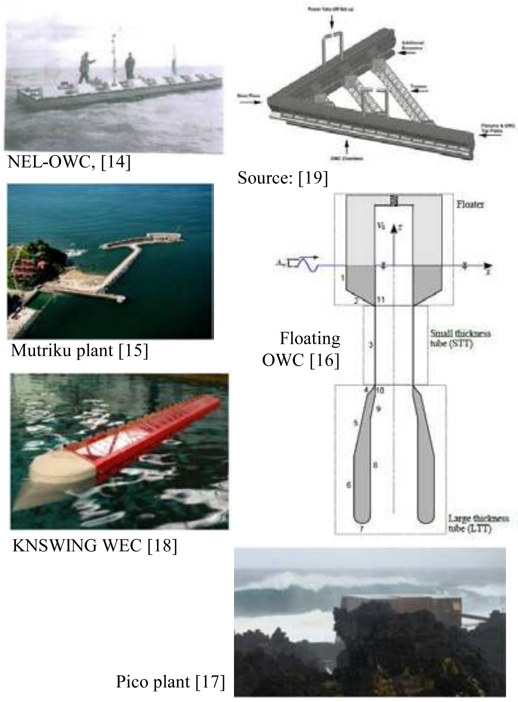

Figure 4: Pictures of the OWC technologies covered by the sources reviewed in section 3.1.1.

- [15] deals with the design and construction of the Mutriku wave power plant, which is a combination of a breakwater with OWCs. The width of each OWC chamber is 6 m. Power performance was assessed through experiments on a 1/40 scale model of the plant, from which annual average pneumatic power capture was estimated to be 175 kW for the whole plant. The offshore wave resource being 26 kW/m, the mean annual CWR is 7 %.

- [16] deals with performance optimisation of a floating OWC using numerical modeling. Three configurations were investigated: (A) 8 m diameter and 24 m draft, (B) 8 m diameter and 36 m draft, (C) 12 m diameter and 24 m draft. Other dimensions and PTO characteristics were numerically optimised to maximise power absorption for a site offshore Portugal. The wave resource is 31 kW/m. Mean CWR is respectively 17 %, 23 % and 21 % for configurations A,B and C (see table 3 of the paper). As seen in figure 4, this device differs from the archetypal OWC in figure 3. Thus, it was included in the database as an OWC variant.

- [17] presents power performance results for the OWC pilot plant installed in Pico island in the Azores. Data had been collected from 2005 to 2010, during which period the plant had been running for approximately 1 700 hours in total. As reported in the source, the mean electrical power was measured to be 28 kW for an offshore wave resource of 38 kW/m. The efficiency of the Wells turbine was estimated to be 31 %. The width of the plant is 12 m, thus the mean annual CWR is 20 %.

- [18] presents results of experiments conducted in Cork (Ireland) for the KNSWING WEC. This device is an attenuator equipped with forty OWC chambers (twenty on the port side and twenty on starboard). The model scale is 1/50, with a length of 3 m. It was tested both in regular and irregular waves. Using this data and the scatter diagram provided in the report, we calculated the mean annual CWR to be 18 % for a 7.5 m wide OWC and a 14 kW/m wave resource. The device was classified as variant of OWC because the OWC chambers are not facing the incident waves, see figure 4.

- [19] presents power performance results for a large V-shaped floating

WEC developed in Ireland. Each arm of the V hosts sixteen OWC chambers. Power absorbed in each OWC chamber is manifolded and drives one single air turbine. The length of each arm is 250 m at full scale. A 1/50 scale model was tested in Cork, in Ireland. Figure 24 of the paper shows the performance of the technology in regular waves. Using this data, we estimated the mean annual CWR to be respectively 12, 14, 15, 12 % for sites with wave resource 15, 23, 27, 36 kW/m. The device was classified as variant of OWC because the OWC chambers are not facing the incident waves, see figure 4.

Power performance results for other OWC wave energy converters can be found in [9], [10] and [11]. These sources are discussed in section 3.1.6.

3.1.2. Overtopping devices

Pictures of the overtopping devices discussed in this section are shown in figure 5.

- Reference [20] deals with the SSG (Sea Slot-Cone Generator) wave energy converter, an overtopping device in which the overtopping water is stored in different basins depending on the wave height. As part of plans to install a 10 meter wide pilot plant in Norway, power performance was investigated through experiments on a 1/60 scale model. The mean annual energy production is estimated to be 320 MWh/y for the Norwegian site where the wave resource is 19.5 kW/m. According to table 1 of source [20], the turbine efficiency is in the order of 85 % and the generator efficiency is 96 %. Thus, the mean absorber power is 45 kW/m and the CWR is 23 %. This device differs from the archetypal overtopping device in figure 3 because it has multiple water reservoirs on top of each other. Thus, it was included in the database as a variant of an overtopping device.

- [21] presents power performance results for the well-known Wavedragon device. Experimental results from sea trials of a scale model at a benign site in Nissum Bredning in Denmark were used in conjunction with numerical models to derive non-dimensional performance of the device. Mean annual CWR was reported to be 27 % for a site with wave resource 6 kW/m and device width 65 m, and 18 % for a site with wave resource 24 kW/m and device width 97 m.

Sea Slot-Cone Generator (SSG) [20]

Wavedragon [21]

Figure 5: Pictures of the overtopping devices covered by the sources reviewed in section 3.1.2.

Figure 6: Pictures of the heaving device technologies covered by the sources reviewed in section 3.1.3.

Power performance results for other overtopping devices can be found in [9] and [10]. These sources are discussed in section 3.1.6.

3.1.3. Heaving devices

Pictures of the heaving devices discussed in this section are shown in figure 6.

- Reference [22] deals with a heaving device. Inspired by the SEACAP technology developed by the Hydrocap company, the device has the form of a torus sliding along the mast of an offshore wind turbine. Mean annual power absorption was calculated for the Yeu site. Several diameters and drafts were considered for the torus, with and without latching control. For reasons explained in section 2, we retained only those results with passive control in the database. Mean CWR, calculated using data from table 2 of the paper, ranges from 3 to 9 % with diameters ranging from 11 to 20 m. This is significantly smaller than the usual mean CWR for devices of that size and operational principle. This may be explained by the fact that the PTO damping coefficient was optimized in order to maximize the power absorption in regular waves for the resonance frequency, not in order to maximize the annual energy absorption with irregular waves.

- [23] presents power performance results obtained using numerical modeling for a heaving device. The WEC is a vertical cylinder with 10 m diameter and 2 m height. It is a simplified version of the OPT technology developed in the US. The PTO damping coefficient was optimized for each sea state. The mean annual absorbed power for year 2010 was estimated to be 77 kW for a site offshore Oregon in the US, where the wave resource was 40 kW/m for that year. The mean annual CWR is 19 %.

- [24] presents experimental results conducted in Denmark for the DEXA WEC. As explained in section 2.3, it may be classified as a variant of a heaving device. A 1/30 scale model was used, with length 2.1 m and width 0.81 m. Power performance results are shown in figure 13 of the paper. Using this data and the wave scatter diagram for Yeu (having wave resource 26 kW/m), the mean annual CWR has been estimated by us to be 8 % with a characteristic diameter of 22 m. The characteristic diameter was calculated according to equation 4.

- [25] presents power performance results for the Norwegian WEC technology Lifesaver, a heaving device. A prototype was installed in 2012 in the UK. The buoy is a torus with outer diameter 16 m and inner diameter 10 m. The paper reports on the experience gathered after one year of full scale sea trials. It also shows the electrical power matrix predicted by the numerical model of the device (table 2). According to the paper, the PTO efficiency is 80 %. Using equation 4, we calculated the characteristic diameter of the device to be 12.5m. Hence, we calculated the mean annual CWR to be 12 % for the 26 kW/m Yeu site.

- [26] presents numerical results for the power performance of a WEC inspired by the Wavestar WEC. It is composed of eight heaving buoys connected to a central fixed platform. Power matrices are determined for various diameters of the heaving buoys. Then, annual mean CWR is calculated for coastal locations all over the world. In table 2 of the paper, the average mean annual CWR is reported to be 10 % for 4 m diameter configuration and 15 % for 15 m diameter configuration.

- [27] is the final report of a technico-economical study for four marine renewable energy technologies: three current turbines and one WEC (RM3). It is a heaving WEC, inspired by the OPT technology. The power matrix was determined using numerical modeling and electricity production calculated for a site offshore California. The wave resource is 34 kW/m. The numerical model was validated against experiments. Electricity production is 700 MWh at this site, assuming 80 % PTO efficiency, 95 % availability and 98 % efficiency in the transmission line. Thus, the mean absorbed power is 108 kW. The diameter of the buoy is 20 m, thus the mean annual CWR is 16 %.

Power performance results for other heaving devices can be found in [9], [10], [11] and [45]. These sources are discussed in section 3.1.6.

3.1.4. Fixed OWSCs

Pictures of the fixed OWSCs discussed in this section are shown in figure 7.

- Reference [28] is the final report of a study of the response and performance of Salter's duck. The device reacts against a fixed reference. It has three degrees of freedom: surge, heave and pitch. It extracts energy from the pitch motion only. It is classified as a variant of fixed OWSC. The report deals with numerical and experimental modeling. Both optimal reactive control and four-term control were implemented, of which only the latter is currently feasible in practice. However, even the four-term control is reactive. Indeed, in figure 5.4 of the report, it can be seen that one of the terms in the four-term control corresponds to a negative spring in pitch. For reasons explained in section 2.2, only CWR for devices with passive control are taken into account in the database. Thus, this reference is not included. However, using power performance results with the four-term control, i.e. graph 4 in figure 6.2 of the report, and according to the methodology explained in section 2, mean CWR estimates for the device were calculated by us, and are provided for information. They are respectively 65 %, 75 %, 79 %, 68 % for a 16, 23, 27, 38 kW/m wave resource, the device width being 30 m.

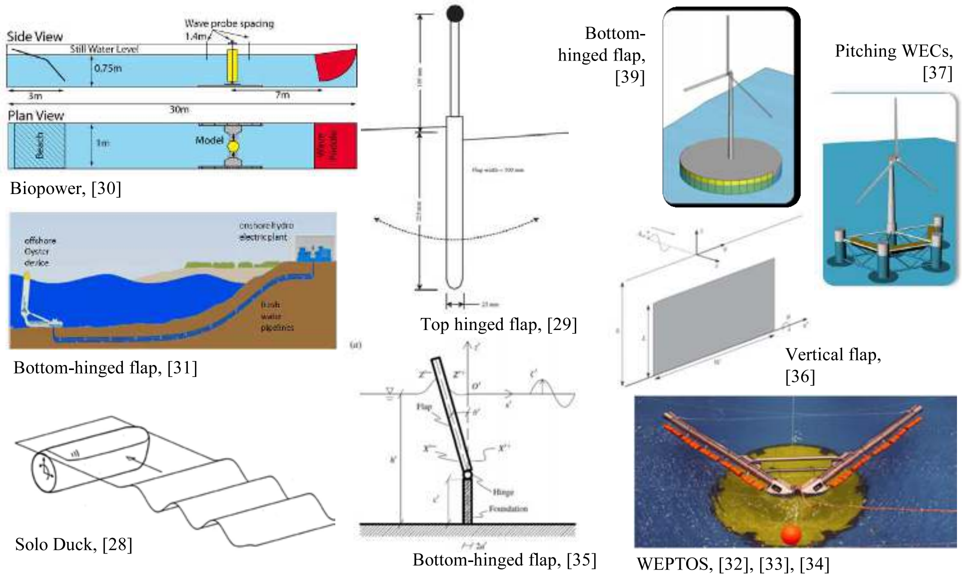

Figure 7: Pictures of the fixed OWSCs covered by the sources reviewed in section 3.1.4.

- Reference [29] reports experimental results for top-hinged flaps. Three water depths were considered: 10, 15 and 22 m. The paper shows results for the CWR in regular and irregular waves (see figures 8 and 9 in the paper). It should be noted that the characteristic dimension in the paper was the cube root of the device volume. Best performance was observed for the smallest water depth, so this was retained in the database. Using data shown in figure 8 of the paper, we calculated the mean annual CWR for a site close to Yeu island offshore the French Atlantic coast, according to the methodology explained in section 2. The wave resource is 25 kW/m, the CWR 25 %, and the width 12 m. The flaps being top-hinged, they are classified as a variant of fixed OWSC.

- Reference [30] reports on experiments conducted on the Biopower technology in Australia. It is classified as a variant of fixed OWSC because it uses a vertical cylinder instead of a vertical flap. The technology was tested experimentally with various ballast configurations in sixteen different random sea states. The first half of the sea states are representative of winter conditions at the EMEC test site, and the other half of summer conditions. Probabilities of occurence of these sea states at EMEC are given in the paper in table 1, allowing calculation of the wave resource in summer and winter conditions: 10 and 67 kW/m, respectively. Table 4 in the paper shows power performance for the summer and winter seasons for each configuration tested, with configuration 5 retained by us as the one with the best performance, namely 41 kW in summer and 130 kW in winter. The device width being 6.6m, the mean CWR is thus 45 %.

- Reference [31] reports power performance for a fixed OWSC in shallow water depth. Figure 7 of the paper shows results of mean CWR derived from experiments conducted in a wave tank at Queen's University Belfast in Northern Ireland. Mean CWR is 35 % for the 6 m width device, increasing with width up to 65 % for a 24 m wide device. The wave scatter diagram used to calculate the mean CWR is not given in the paper.

- References [32], [33] and [34] present results of experiments of the WEPTOS technology. The WEPTOS is composed of a V-shaped platform and WECs similar to Salter's ducks. The ducks are mounted on a common spine on each branch of the V. They are classified as variant of the fixed OWSC. A scale model was tested in 2011 in Spain and the performance of the machine was measured in random waves, as well as bending moments in the structure and mooring forces. Building on experimental results, prototype performance at a scaling ratio of 1/15 was predicted in [32] at the Hanstholm site in Denmark where the wave resource is 6 kW/m. The mean annual CWR is thus expected to be 12 % with a WEC width of 3.6 m. Using the same experimental data, prototype performance at scaling ratios of 1/12, 1/15, 1/20 and 1/25 is predicted in [33] at the Hanstholm site (Table 2 of [33])and at site in the Danish North Sea where the wave resource is 16 kW/m (Table 3 of [33]). In table 2 of source [34], mean annual power production is reported for two other sites in Denmark, one site in France and the EMEC test site in Scotland. 90 % PTO efficiency and 98 % availabilty was used in [34] according to private communication with the authors. The performance results from references [32], [33] and [34] are summarized in table 1.

- [35] is a mathematical and numerical study of a fixed OSWC in a canal.

Technology	operational principle	η_1	Dimension (m)		Resource (kW/m)
WEPTOS	Variation of fixed OWSC	8	2.9	Width	6
		10	2.9	Width	16
		12	3.6	Width	6
		12	3.6	Width	16
		19	4.8	Width	6
		15	4.8	Width	16
		15	5.4	Width	9
		25	6.0	Width	6
		19	6.0	Width	16
		32	8.3	Width	16
		22	9.6	Width	29
		25	9.6	Width	26

Table 1: Summary of performance results for the WEPTOS technology studied in [32], [33] and [34]

The problem is equivalent to an infinite line array of devices facing the incident waves. The device is inspired by the Aquamarine/Oyster. Figure 8 in the paper shows CWR for three device widths. The canal width is fixed at 91.6 m. According to the method described in section 2, we calculated the mean actual CWR for the Yeu site, having 26 kW/m wave resource, to be 22 % for the 6 m wide device, 40 % for the 12 m device and 55 % for the 18 m device.

- [36] presents numerical results for the power performance of a combined wind and wave energy platform. It is composed of a large floating barge with twenty vertical flaps on its wave facing side and a 5 MW wind turbine mounted on top of it. The floating barge is large and stable, thus the WECs can be classified as a variant of fixed OWSCs. The power matrix was determined using numerical modeling. Table 4 of the paper shows that the hydrodynamic efficiency is 72 % for a 26 kW/m site using the barge diameter (100 m) as the reference width. Using the WEC width (10 times 16 m), the mean annual CWR is calculated to be 45 %.

- [37] shows numerical results for the power performance of a combined wind and wave energy platform. It is composed of a semi-submersible platform with a 5 MW wind turbine mounted on top of it. Twelve pitching WECs are installed on the wave facing braces of the platform. The width of the WECs is 9 m. Based on the geometry of the WECs, they are classified as a variant of fixed OWSC. The power matrix was determined using numerical modeling. Table 4 of the paper shows that the mean annual CWR hydrodynamic efficiency is 61 % for a 26 kW/m site.

- [38] presents numerical results for the power performance of submerged and surface piercing bottom-hinged plate wave energy converters. The devices are inspired by the Aquamarine/Oyster and the AW-Energy/WaveRoller. Influence of the flap height to water depth ratio and flap width to water depth ratio are investigated. Figure 14 in the paper shows CWR for a surface piercing flap in irregular waves (with Pierson-Moskowitz spectrum) for five flap widths. Figure 19 in the same paper shows CWR for a 20 m wide flap for five flap heigths. The water depth is 10 meters. According to the method described in section 2, we calculated the mean actual CWR for the Yeu site. Best performance was observed for the surface piercing flap, so this was retained in the database (the reference highlights the importance of having a surface-piercing device for the maximization of the wave energy absorption for OWSCs). The CWR estimates are 17, 36, 72 and 64 % for flap widths of respectively 5, 10, 20 and 50 meters and for a 26 kW/m site.

Power performance results for other OWSCs can be found in [11], [44] and [45]. These sources are discussed in section 3.1.6.

3.1.5. Floating OWSCs

Pictures of the floating OWSCs discussed in this section are shown in figure 8.

- References [39] and [40] reports on experiments conducted on the Langlee technology, consisting of oscillating flaps mounted on a floating structure. Experiments were conducted at Aalborg University in Denmark. Experiments carried out at small scale in order to determine the power performance of these devices in five random sea states with significant height ranging from one to five meters. Mean annual CWR were obtained by weighting power performance for each sea state with its probability of occurence at a site offshore Denmark. The mean annual resource was 16 kW/m. Table 6 of source [39] shows that the mean CWR was found to be 7 % for a device width 25 m and 9 % for devices width 37.5 m and 50 m. Note that the total flap width has been taken into account in the CWR. [40] reports on a second round of experiments conducted on the same technology. The tested geometry

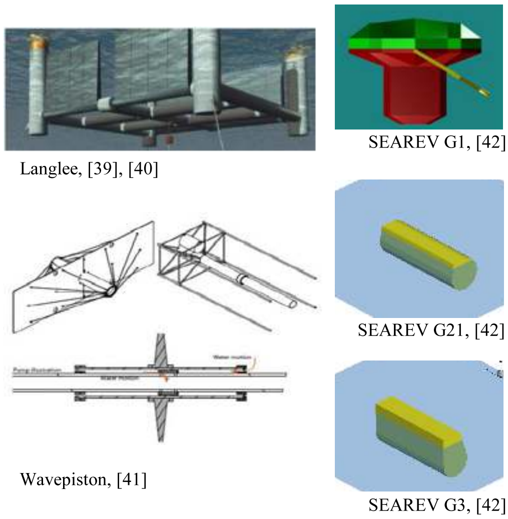

Figure 8: Pictures of the floating OWSCs covered by the sources reviewed in section 3.1.3.

differed from [39]in that: surface piercing flaps were used. This was found to increase efficiency compared to a fully submerged flap configuration. Buoyancy of the flaps was also found to have a large impact on efficiency. Tables 3 and 4 of [40] show the estimates of yearly power production for several scales of the device (1/20, 1/40, 1/60) and two locations. For the Danish North Sea site, whose wave resource is 16 kW/m, yearly power production is 620 MWh/y for a device width 25 m. For the Runde site, whose wave resource is 21 kW/m, yearly power production is respectively 420 MWh/y, 1870 MWh/y and 3720 MWh/y for devices width 25 m, 50m and 100m. The total width of flaps for the device being twice the device width, the CWR is 9 % for the site with 16 kW/m resource: for the site with 21 kW/m resource, the CWR is respectively 5 %, 10 % and 10% for devices width 25 m, 50 m and 100 m.

- Reference [41] reports on experiments in Denmark using the Wavepiston technology. This device is made of vertical plates facing the waves and sliding along one long common axis, and can be classified as a variant of floating OWSC. As for references [9] and [39], the device was tested for five representative sea states. The mean CWR was obtained by weighting performance results by their probabilities, and mean CWR is 8 % for a 15 m wide device (see table 3 of the paper) and a wave resource of 12 kW/m. Another site offshore Italy was also considered, for which mean CWR is 15 % for a wave resource of 3.5 kW/m.

- Reference [42] deals with the development of the SEAREV WEC technology. The SEAREV device absorbs wave power through pitch motion; as such, it can be classified as a variant of floating OWSC. Mean annual absorbed power with and without control was derived using numerical modeling. In the database, we retained only results with passive control. Three versions of the SEAREV technology are presented in the source [42]. They are labelled SEAREV G1, SEAREV G21 and SEAREV G3. The width of SEAREV G1 is 13.6 m, whereas it is 30 m for SEAREV G21 and SEAREV G3. According to data shown in tables 1, 2 and 5 of [42], the mean CWR are respectively 20 %, 16 % and 25 % for SEAREV G1, SEAREV G21 and SEAREV G3 for a site with 25 kW/m resource.

Power performance results for other floating OWSCs can be found in [11] and [44]. These sources are discussed in section 3.1.6.

3.1.6. Sources considering technologies with various working principles

- Reference [43] is a report presenting results of a technical-economical assessment of ten wave energy converters which were developed in the UK in the late 70s and early 80s. Six of the devices are OWCs or variants of OWCs, the others being variants of fixed OWSCs, including the famous Edinburgh Duck and Bristol Cylinder. The devices are depicted in figure 9. Power performance was assessed using experiments in directional random waves, except in the case of the NEL Terminator device, for which numerical models were used. Scale models of the devices were tested for 46 sea states representative of the South Uist offshore site in the UK. Mean annual CWR for each technology are shown in device data sheets in section 5 of source [43], and recalled in table 2. It may be observed that power performance for the Vicker's terminator, the Vicker's Attenuator and the Lancaster Flexible Bag is significantly lower than for other devices with same operational principle and comparable dimensions. According to [43], this is due to the use of manifolding in the PTO.

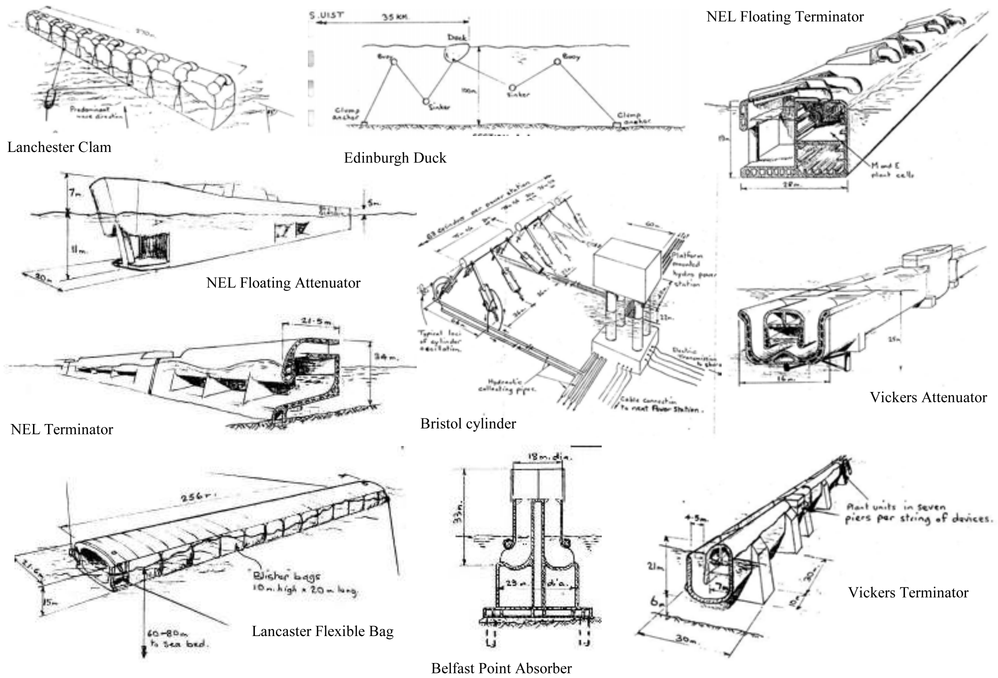

Figure 9: Pictures of wave energy converters investigated in [43].

Technology	operational principle	η_1	Dimension (m)		Resource (kW/m)
NEL Terminator	OWC	55	22	Width	30
NEL Floating Terminator	OWC	24	22	Width	54
NEL Floating Attenuator	OWC	41	20	Width	54
Vicker's Terminator	Variant of OWC	34	30	Width	36
Vicker's Attenuator	Variant of OWC	16	30	Width	36
Belfast Point Absorber	Variant of OWC	35	29	Outer diameter	42
Edinburgh Duck	Variant of OWSC	47	37	Width	54
Bristol Cylinder	Variant of OWSC	46	75	Width	48
Lancaster Flexible Bag	Variant of OWSC	9	20	Width	51
Lanchester Clam	Variant of OWSC	23	27	Width	51

Table 2: Performance results for technologies studied in [43]

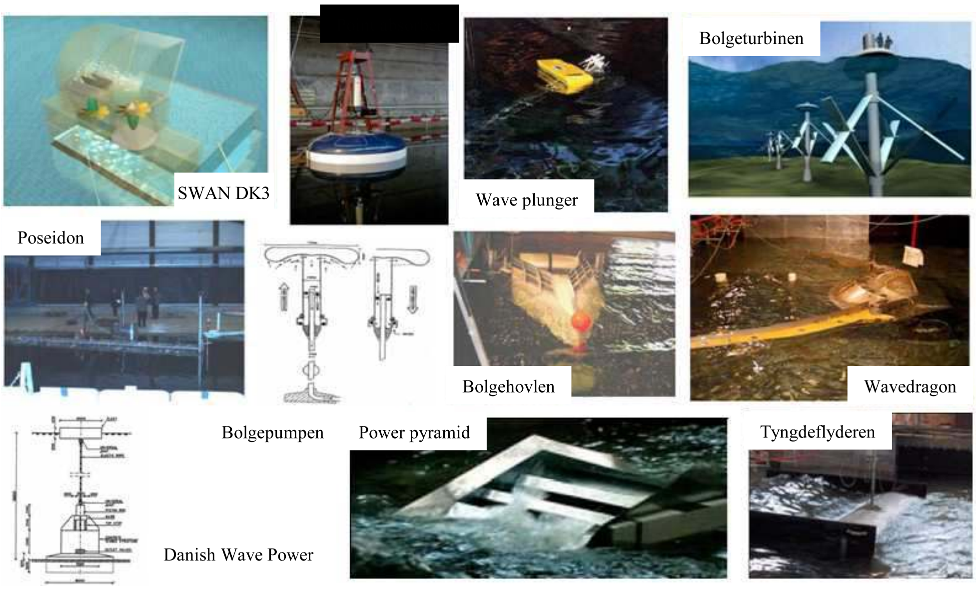

Figure 10: Pictures of wave energy converters investigated in [9].

- Reference [9] is the final report of a research program conducted in Denmark from 1997 to 2002. The aim of the program was to investigate a large number of WEC technologies. Twelve devices were considered: one floating OWC, several wave activated bodies, several overtopping devices and one wave turbine. The devices are depicted in figure 10. Experiments were conducted at small scale in order to determine the power performance of these devices in five random sea states with significant height ranging from one to five meters. Mean annual CWR were obtained by weighting power performance for each sea state with its probability of occurence at a site offshore Denmark. The scatter diagram resulted from [56]. The mean annual resource was 16 kW/m. Mean annual CWR η_1 for each technology, directly taken from table 8.6 of source [9], is recalled in table 3. Note that for some cases, a few designs of the same technology were tested: in these cases, we retained only that with best performance. For heaving devices, we calculated the dimension using equation 4.

- Reference [10] is a report presenting results from a study conducted by E2I EPRI on the technico-economical feasability of wave energy conver-

Technology	operational principle	η_1	Dimension (m)		Resource (kW/m)
Swan DK3	OWC	20	16	Width	16
Bølgehovlen	Overtopping	8	10	Diameter	16
Power pyramid	Variant of overtopping	12	125	Width	16
Wavedragon	Overtopping	23	259	Width	16
Sucking Sea Shaft	Variant of overtopping	3	125	Width	16
Bølgepumpen	Variant of heaving device	6	5	Diameter	16
Point absorber	Heaving device	14	10	Diameter	16
DWP system	Heaving device	20	10	Diameter	16
Tyngdeflyderen	Variant of heaving device	12	30	Characteristic diameter	16
Wave plunger	Variant of fixed OWSC	16	15	Width	16
Poseidon	Unknown	27	420	Width	16
Bølgeturbinen	Wave turbine	4	15	Rotor diameter	16

Table 3: Performance results for technologies studied in [9]

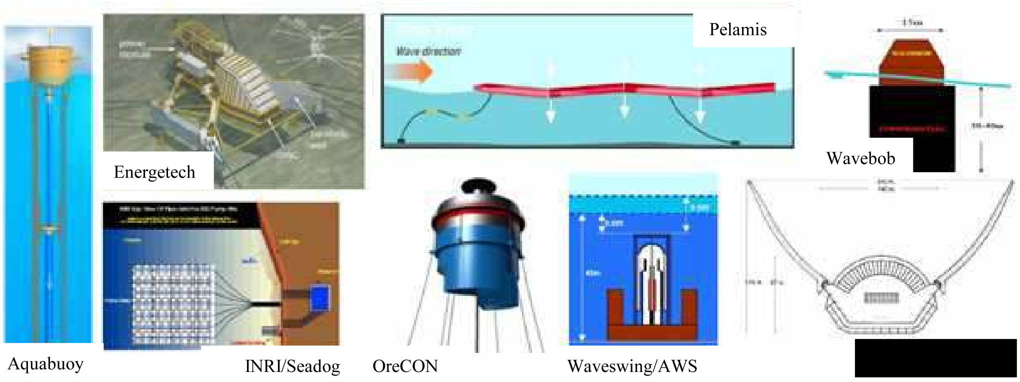

Figure 11: Pictures of wave energy converters investigated in [10].

Technology	operational principle	η_1	Dimension (m)		Resource (kW/m)
AquaEnergy/ AquaBuOY	heaving device	[10-26]	6	Diameter	[12-26]
Energetech	OWC	58	35	Width	[12-26]
INRI/SEADOG	heaving device	[16-24]	5.7	Diameter	[12-26]
Ocean Power Delivery/Pelamis	Variant of heaving device	[14-21]	15	Characteristic diameter	[12-26]
ORECON/ MR1000	OWC	[176-281]	32	Diameter	[12-26]
TeamWork/AWS	Variant of heaving device	[138-205]	9.5	Diameter	[12-26]
Wavebob	heaving device	[40-51]	15	Diameter	[12-26]
Wavedragon	overtopping	[21-26]	24	Width	[12-26]

Table 4: Performance results for technologies studied in [10]

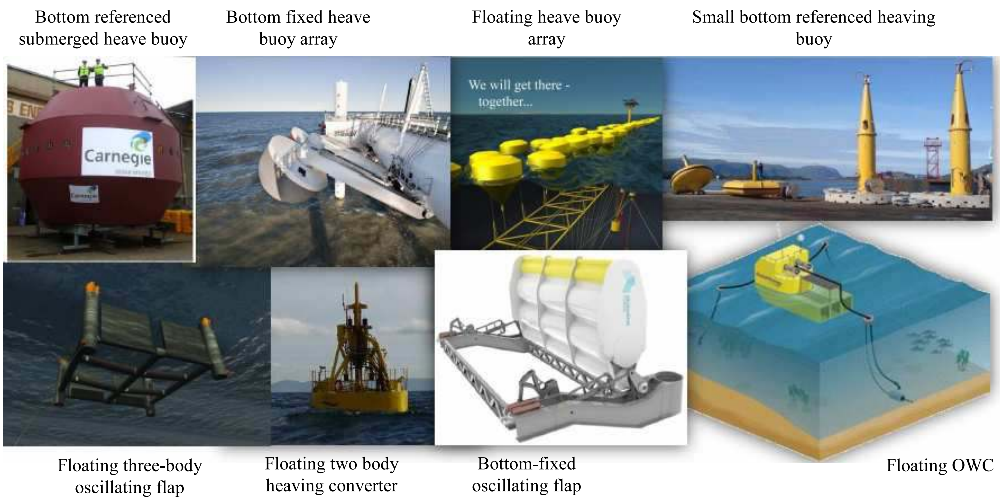

Figure 12: Pictures of wave energy converters investigated in [11].

sion in the US in 2004. Eight technologies were assessed: Ocean Power Delivery (currently Pelamis Wave)/Pelamis, Energetech, Wavedragon, Waveswing/AWS, Wavebob, Aquaenergy/AquaBuOY, OreCON and INRI/SEADOG. The devices are depicted in figure 11. Power production calculations were based on data and a power matrix provided by the technology developers. Results have been extracted from the report and summarized in table 4.

- Reference [11] presents the results of a numerical benchmarking study of a selection of eight wave energy technologies inspired by devices which are or were being developed. The selection includes a float-

Technology	operational principle	η_1	Dimension (m)		Resource (kW/m)
Small bottom-referenced heaving buoy	Variant of heaving device	[3-4]	3	Diameter	[15-37]
Bottom-referenced submerged heave-buoy	Heaving device	[8-13]	7	Diameter	[13-34]
Floating-two body heaving converter	Heaving device	[27-36]	20	Diameter	[15-37]
Bottom-fixed heave-buoy array	Heaving device	[12-17]	5	Diameter	[13-34]
Floating heave-buoy array	Heaving device	[6-11]	8	Diameter	[15-37]
Bottom-fixed oscillating flap	Fixed OWSC	[58-72]	26	Width	[13-34]
Floating three-body oscillating flap	Floating OWSC	[7-13]	19	Width	[15-37]
Floating OWC	OWC	[22-35]	24	Width	[15-37]

Table 5: Performance results for technologies studied in [11]

ing OWC, several heaving devices, one floating OWSC and one fixed OWSC. The devices are shown in figure 12. The study used numerical modeling: Wave to Wire (W2W) models were developed and used to derive the power matrix of each technology. Then, the mean annual power absorption was calculated at five European possible deployment locations whose wave resource ranges from 15 to 80 kW/m. Depending on the technology, it was shown that the mean CWR may depend significantly on the resource, up to a factor of three. However, the lowest mean CWR was always obtained for the most energetic site (80 kW/m at Belmullet, Ireland). As this is much higher than the usual global figures for wave resource (10-40 kW/m, see [58]), we did not take it into account. Table 5 summarizes mean CWR for the eight technologies extracted from figures 12 to 19 of [11].

- [44] presents numerical results for the power performance of fixed and floating OWSCs. Three configurations are considered : (A) one flap mounted on a supporting frame, (B) two flaps that sit side by side and (C) two flaps, one in the front and one in the back. The devices are depicted in figure 13. In all configurations, the flap width is 25 m. Numerical modeling was used to derive power matrices for each configuration and for different mooring configurations (fixed supporting frame, taut mooring and slack mooring). With the fixed supporting frame, the devices are classified as variants of fixed OWSC because the flap height is not close to the water depth. The wave scatter diagram is shown in table 4. The wave resource is 30 kW/m. Annual average

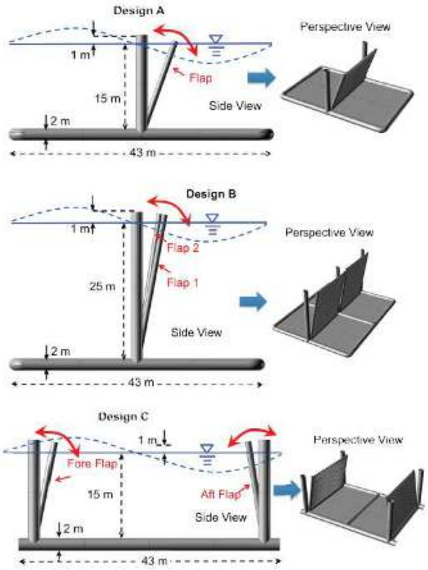

Figure 13: Pictures of wave energy converters investigated in [44].

electrical power is shown in figure 7 of the paper. 80 % PTO efficiency is assumed as well as 95 % availability and 98 % efficiency in the transmission line. Table 6 shows the mean annual absorbed power and CWR for the configurations considered in the paper.

- [45] presents numerical results for the power performance of a two-body heaving device and a fixed OWSC. The devices are shown in figure 14. The heaving device is 15 m wide. On page 99 of source [45], it is reported that the average electric power is 82 kW, with hydraulic PTO efficiency of 72 %. The wave resource at the site being 31 kW/m, the mean annual CWR is 25 %. For the fixed OWSC, the width is 25.5 m. It is reported (page 108 of source [45] that the average electric power is 170 kW with hydraulic PTO efficiency of 75 %. The wave resource at the site being 18 kW/m, the mean annual CWR is 49 %.

3.2. Summary table

The data collected for mean annual CWR is synthesized in tables 7, 8 and 9. The WECs have been grouped in ten categories as discussed in section 2.3:

Technology	**operational principle**	**Mean absorbed power per flap**	η_1	**Dimension (m)**		**Resource (kW/m)**
Vertical flaps on fixed supporting frame	Variant of fixed OWSC	240	31	25	Width	30
		450	37	50		
		220	30	25		
Vertical flaps on supporting frame with taut moorings	Floating OWSC	138	18	25	Width	30
		266	18	50		
Vertical flaps on supporting frame with slack moorings	Floating OWSC	58	8	25	Width	30
		128	8	50		
		158	21	25		

Table 6: Performance results for technologies studied in [44]

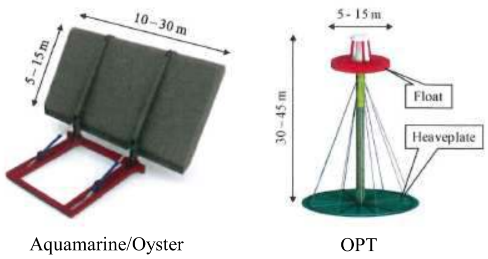

Figure 14: Pictures of wave energy converters investigated in [45].

OWCs and variants, overtopping devices and variants, heaving devices and variants, fixed OWSC and variants, floating OWSC and variants. Devices not belonging to any of these categories were not included in the tables. In these, the devices are labeled by their commercial names when available, or by the description of their operational principle. CWR is reported alongside the corresponding wave resource for which it was measured and the dimension on which the CWR was built.

Where available, information relating to how the CWR was obtained (model tests, numerical modeling or measurements on full scale prototype) is also reported. In more than half of the cases, CWR were obtained through experiments at model scale or prototype scale.

The tables also indicate whether the source is independent from the technology developer. 'Developer' indicates that the information comes from the technology developer itself whereas 'independent' means that the CWR was established by an independent body (usually a research lab).

4. Discussion

In total, 156 measurements of CWR were collected. Figure 15 shows the distribution of measurements as a function of the WEC categories. The category for which the most performance information was found (56 measurements) was heaving devices, followed by fixed OWSCs and OWCs. This is somewhat surprising, as OWCs have been studied for more than 30 years, whereas fixed OWSCs have only started developing over the last decade. The least information was found for floating OWSCs and overtopping devices.

Some of the measurements are believed to be unreliable (lines in italics in tables 7 and 8). Indeed, for the AWS and the ORECON/MR1000, the CWR is five to ten times larger than other similar technologies. Because the available source information does not provide an explanation for these discrepancies, these measurements were discarded from further analysis. The Hydrocap/SEACAP device was also discarded because it is five times smaller than device of similar dimensions, and because as explained before, the performance is small because the PTO damping coefficient was optimized for the resonant period in regular waves, and not for the mean annual power absorption in irregular waves.

Moreover, for some of the technologies, CWR is available for several levels of wave resource. The CWR for the level of wave resource closest to 25 kW/m was selected as the most representative [58].

Category	Technology	η_1 (%)	Resource (kW/m)	Characteristic dimension(m)		Ref.	Methods	Source
Oscillating Water Column	NEL Terminator	55	30	22	Width	[43]	Model tests	Independent
	NEL Floating Terminator	24	54	22	Width	[43]	Model tests	Independent
	NEL Floating Attenuator	41	54	20	Width	[43]	Model tests	Independent
	Swan DK3	20	16	16	Width	[9]	Model tests	Independent
	Energetech	72 58 58 33	12 21 26 15	35	Width	[10]	N/A	Developer
	ORECON/ MR1000	*213* *209* *176* *281*	*12* *21* *26* *15*	*32*	*Diameter*	*[10]*	*N/A*	*Developer*
	Floating OWC	23 32 35 24	15 22 27 37	24	Width	[11]	N/A	Independent
	NEL-OWC	22 27 29 23	16 23 27 37	30	Width	[14]	Sea trials	Developer
	Mutriku wave power plant	7	26	6	Width	[15]	Model tests	Developer
	Pico	20	38	12	Width	[17]	Prototype	Independent
Variant of oscillating water column	Vickers Terminator	34	36	30	Width	[43]	Model tests	Independent
	Vickers Attenuator	16	36	30	Width	[43]	Model tests	Independent
	Belfast Point absorber	35	42	29	Diameter	[43]	Model tests	Independent
	Floating OWC	17 23	31	8 12	Diameter	[16]	Numerical modelling	Independent
	KNSWING	18	14	7.5	Width	[18]	Model tests	Developer
	Floating OWC	12 14 15 12	15 23 27 36	12.5	Width	[19]	Model tests	Independent
Overtopping devices	Bolgehovlen	8	16	10	Diameter	[9]	Model tests	Independent
	Wavedragon	23	16	259	Width	[9]	Model tests	Independent
	Wavedragon	26 23 21 22	12 21 26 15	300	Width	[10]	N/A	Developer
	Wavedragon	27 18	6	65 97	Width	[21]	Model tests	Developer
Variant of overtopping devices	Power pyramid	12	16	125	Width	[9]	Model tests	Independent
	Sucking Sea Shaft	3	16	125	Width	[9]	Model tests	Independent
	SSG	23	19.5	10	Width	[20]	Model tests	Developer

Table 7: Summary table of energy performance of wave energy converters

Category	Technology	η_1 (%)	Resource (kW/m)	Characteristic dimension(m)		Ref.	Methods	Source
Heaving devices	Point absorber	14	16	125	Width	[9]	Model tests	Independent
	DWP system	20	16	10	Diameter	[9]	Model tests	Independent
	AquaEnergy/ AquaBuOY	20 17 14 21	12 21 26 15	6	Diameter	[10]	N/A	Developer
	INRI/SEADOG	24 16 16 21	12 21 26 15	5.7	Diameter	[10]	N/A	Developer
	Wavebob	40 51 46 45	12 21 26 15	15	Diameter	[10]	N/A	Developer
	Small bottom-referenced heaving buoy	4 4 4 3	15 22 27 37	3	Diameter	[11]	Numerical modelling	Independent
	Floating two-body heaving converter	27 29 36 27	15 22 27 37	20	Diameter	[11]	Numerical modelling	Independent
	Bottom-fixed heave-buoy array	14 16 17 12	13 19 22 34	5	Diameter	[11]	Numerical modelling	Independent
	Floating heave-buoy array	11 11 11 6	15 22 27 37	8	Diameter	[11]	Numerical modelling	Independent
	Two-body heaving device	25	31	15	Diameter	[45]	Numerical modelling	Independent
	Hydrocap/ SEACAP	*4* *3* *6* *6* *9*	*25*	*10* *11* *15* *16.5* *20*	*Diameter*	*[22]*	*Numerical modelling*	*Independent*
	Inspired by OPT	19	40	10	Diameter	[23]	Numerical modelling	Independent
	LifeSaver	12.5	27	12.5	Diameter	[25]	Prototype	Developer
	Inspired by Wavestar	10 15	N/A	4 15	Diameter	[26]	Numerical modelling	Independent
	Lifesaver	12	26	12.5	Characteristic diameter	[25]	Prototype	Developer
	RM3	16	34	20	Diameter	[27]	Numerical modelling	Independent
Variant of heaving devices	Bolgepumpen	6	16	5	Diameter	[9]	Model tests	Independent
	Tyngdeflyderen	12	16	30	Characteristics diameter	[9]	Model tests	Independent
	Pelamis	21 15 14 18	12 21 26 15	15	Characteristic diameter	[10]	N/A	Developer
	AWS	*138* *205* *142* *145*	*12* *21* *26* *15*	*9.5*	*Diameter*	*[10]*	*N/A*	*Developer*
	Bottom-referenced submerged heave-buoy	9 13 13 8	13 19 22 34	7	Diameter	[11]	Numerical modelling	Independent
	DEXA	8	26	22	Characteristic diameter	[24]	Model tests	Independent

Table 8: Summary table of energy performance of wave energy converters (continued)

Category	Technology	η_1 (%)	Resource (kW/m)	Characteristic dimension(m)		Ref.	Methods	Source
Fixed OWSC	Bottom-fixed oscillating flap	61 68 72 58	13 19 22 34	26	Width	[11]	Numerical modelling	Independent
	Bottom-fixed oscillating flap	49	18	25.5	Width	[45]	Numerical modelling	Independent
	Biopower	45	38.5	6.6	Diameter	[30]	Model tests	Developer
	OWSC	35 52 62 65	N/A	6 12 18 24	Width	[31]	Model tests	Developer
	Inspired by Oyster	22 40 55	26	6 12 18	Width	[35]	Numerical modelling	Independent
	Surface piercing flap	17 36 72 64	26	5 10 20 50	Width	[38]	Numerical modelling	Independent
Variant of fixed OWSC	Edinburgh Duck	47	54	37	Width	[43]	Model tests	Independent
	Bristol Cylinder	46	48	75	Width	[43]	Model tests	Independent
	Lancaster flexible bag	9	51	20	Width	[43]	Model tests	Independent
	Lanchester Clam	23	51	27	Width	[43]	Model tests	Independent
	Wave plunger	16	16	15	Width	[9]	Model tests	Independent
	Vertical flaps on fixed supporting frame	31 37 30	25 50 25	30	Width of each flap	[44]	Numerical modelling	Independent
	Top-hinged flaps	25	25	12	Width	[29]	Model tests	Independent
	WEPTOS	10 12 15 15 19 32 25	16 16 16 9 16 16 26	2.9 3.6 4.8 5.4 6 8.3 9.6	Width	[32], [33], [34]	Model tests	Independent
	Combined wind and wave energy platform	45	26	16	Width	[36]	Numerical modelling	Independent
	Combined wind and wave energy platform	61	26	9	Width	[37]	Numerical modelling	Independent
Floating OWSC	Floating three-body oscillating flap	9 13 13 7	15 22 27 37	19	Width	[11]	Numerical modelling	Independent
	Vertical flaps on supporting frame with taut moorings	18 18	25 50	30	Width	[44]	Numerical modelling	Independent
	Vertical flaps on supporting frame with slack moorings	8 8 21	25 50 25	30	Width	[44]	Numerical modelling	Independent
	Langlee	7 5 9 9 10 10	16 21 16 16 21 21	25 25 37.5 50 50 100	Width	[39],[40]	Model tests	Independent
Variant of floating OWSC	Wavepiston	15 8	12 3.5	15	Width	[41]	Model tests	Independent
	SEAREV G1 SEAREV G21 SEAREV G3	20 16 25	25	13.6 30 30	Width	[42]	Numerical modelling	Developer

Table 9: Summary table of energy performance of wave energy converters (continued)

		OWCs	Overtopping devices	Heaving devices	Fixed OWSCs	Floating OWSCs
Capture width ratio (%)	Mean	29	17	16	37	12
	STD	13	8	10	20	5
Characteristic dimension (m)	Mean	20	124	12	18	33
	STD	10	107	7	14	24

Table 10: Mean and standard deviation of CWR and characteristic dimension for each WEC category

After screening, 90 measurements were retained for further analysis. The two categories with the most measurements in the screened data, including variants, are fixed OWSCs and heaving devices, with 30 and 24 measurements respectively. OWCs, floating OWSCs and overtopping devices had 16, 12 and 8 measurements, respectively. Excluding variants, the categories with most measurements are heaving devices and fixed OWSCs, both with 14 measurements. OWCs, floating OWSCs and overtopping devices had 9, 8 and 5 measurements, respectively.

Statistical analysis was performed. For each category, table 10 shows the mean and the standard deviation for both the CWR and the characteristic dimension of the WECs. Variants were taken into account. According to the mean, the most efficient category of WECs is fixed OWSCs with a mean CWR of 37 %. The second most efficient WECs are OWCs (mean CWR of 29%), followed by overtopping devices (17 %), heaving devices (16 %) and floating OWSCs (12 %).

One can see that standard deviations of the CWR are large - typically, half of the mean CWR. This shows that, within a given category, the power performance of devices can differ widely. However, the mean CWR gives a good indication of the typical order of magnitude of the power performance of each of these categories.

From table 10, it can also be seen that heaving devices are typically the smallest WECs (having mean characteristic dimension 12 m). The second smallest are the fixed OWSCs (18m) and the OWCs (20m), followed by the floating OWSCs (33m) and the large overtopping devices (124m).

Figure 16 shows the CWR as a function of the WEC characteristic dimension and the WEC category. Although the level of scattering is large, trends can be identified:

- Floating OWSCs and overtopping devices appear to be the least efficient devices, in terms of absorbing wave energy.

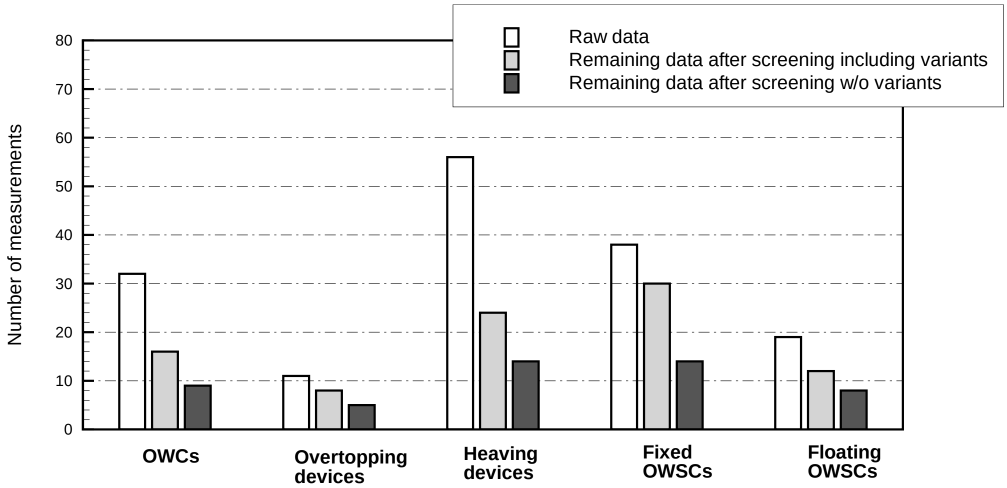

Figure 15: Number of measurements per category of WECs.

- Fixed OWSCs appear to be the most efficient devices.
- Heaving devices and OWCs appear to be in the middle of the efficiency range.

Being able to identify these trends from the data gives confidence in the classification that has been used (OWCs, overtopping devices, heaving devices, fixed and floating OWSCs). It indicates that the classification reflects rather well the underlying physical principles that lead to wave energy absorption by these WEC technologies.

It can be seen from figure 16 that CWR increases with the characteristic dimension for OWCs, heaving devices, overtopping devices and fixed OWSCs. Linear regression was performed for these categories on the most representative measurements points (i.e variants were not taken into account).

It yields a reasonable fit for the OWCs and the heaving devices, the coefficient of determination being 0.57 for the OWCs and 0.42 for the heaving devices. For overtopping devices, the linear fit is only approximate, the coefficient of determination being 0.21. This is due to the limited number of measurement points and an outlier having high CWR (27 %) for the width of 65 m. One may note that the wave resource corresponding to this measurement point is much smaller (6kW/m) than for the other measurement

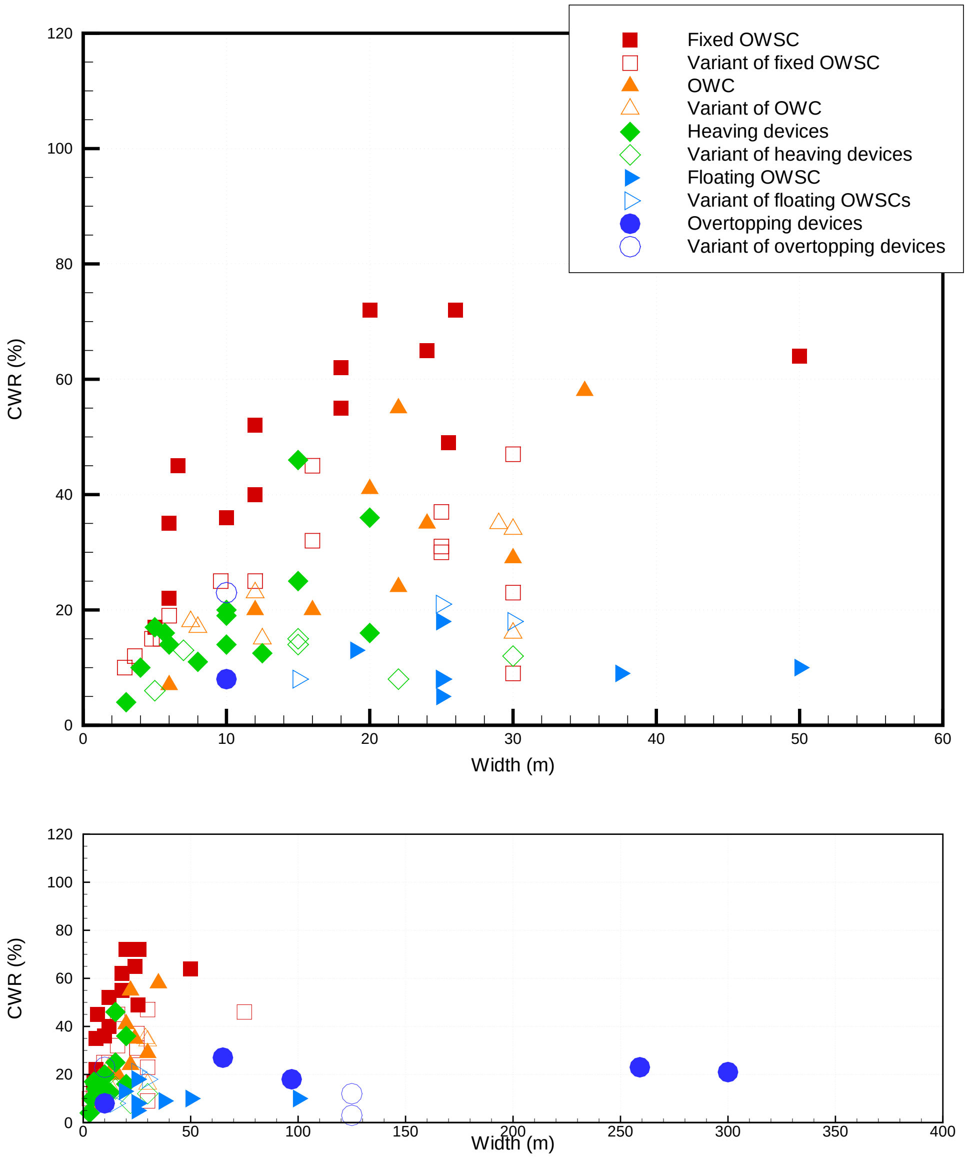

Figure 16: CWR as a function of the WEC characteristic dimension and the WEC category. Top figure zooms in on the subdomain [0,60] m part of the bottom figure.

	Best fit	95 % confidence interval
OWCs	$\tilde{\eta}_1 = 1.4B + 2.1\ ,\ B \in [0, 40]$	$\tilde{\eta}_1 \pm 30\sqrt{1.1 + \frac{(B-21)^2}{81}}$
Overtopping devices	$\tilde{\eta}_1 = 0.026B + 15.6\ ,\ B \in [0, 320]$	$\tilde{\eta}_1 \pm 26\sqrt{1.2 + \frac{(B-146)^2}{7230}}$
Heaving devices	$\tilde{\eta}_1 = 1.3B + 5.6\ ,\ B \in [0, 20]$	$\tilde{\eta}_1 \pm 21\sqrt{1.1 + \frac{(B-10)^2}{31}}$
Fixed OWSCs	$\tilde{\eta}_1 = 1.9B + 20.5,\ B \in [0, 20]$	$\tilde{\eta}_1 \pm 25\sqrt{1.1 + \frac{(B-15)^2}{61}}$
Floating OWSCs	$\tilde{\eta}_1 = 8.5,\ B \in [0, 100]$	$\tilde{\eta}_1 \pm 12\sqrt{1.1 + \frac{(B-53)^2}{1090}}$

Table 11: Best fit equations and 95% confidence interval for each WEC category

points (in the order of 20 kW/m, see table 7). It may be expected that the same device at a site with larger wave resource has a smaller CWR, thus more in agreement with the linear fit.

For fixed OWSCs, it can be observed in 16 that CWR increases with width for widths between 0 up to 30 m. In the database 9, it can be seen that several devices in this category have a CWR greater than 50 % for widths in the order of 20 to 30 m. On the other hand, it is well known from [50] that the maximum CWR is 50 % for devices whose width is greater than the wavelength. Consequently, the increase in CWR with width that can be seen in figure 16 for fixed OWSCs must be valid only for small widths. When further increasing the width, the CWR must reach a maximum and then decrease below 50 % for long devices. This is in agreement with the outlier with width 50 m, whose CWR is smaller than similar devices with half its width. Thus, linear fit was performed only on measurements points with width less than 30 m for fixed OWSCs. It yields a reasonable fit, the coefficient of determination being 0.69.

For floating OWSCs, there is no clear relationship between the CWR and the characteristic dimension. For these categories, the best fit appears to be the mean value of the data.

For each category, table 11 shows the best fit equations and the 95% confidence interval, calculated according to [57]. Figure 17 shows, for each category, the data points, the best fit equations and the 95% confidence interval. One can see that all data points are covered by the confidence interval. For each category, devices which are variants of the operational principle have also been plotted (empty symbols). Again, all these points except one are covered by the confidence interval. This gives confidence in the classification choices that have been made in this work.

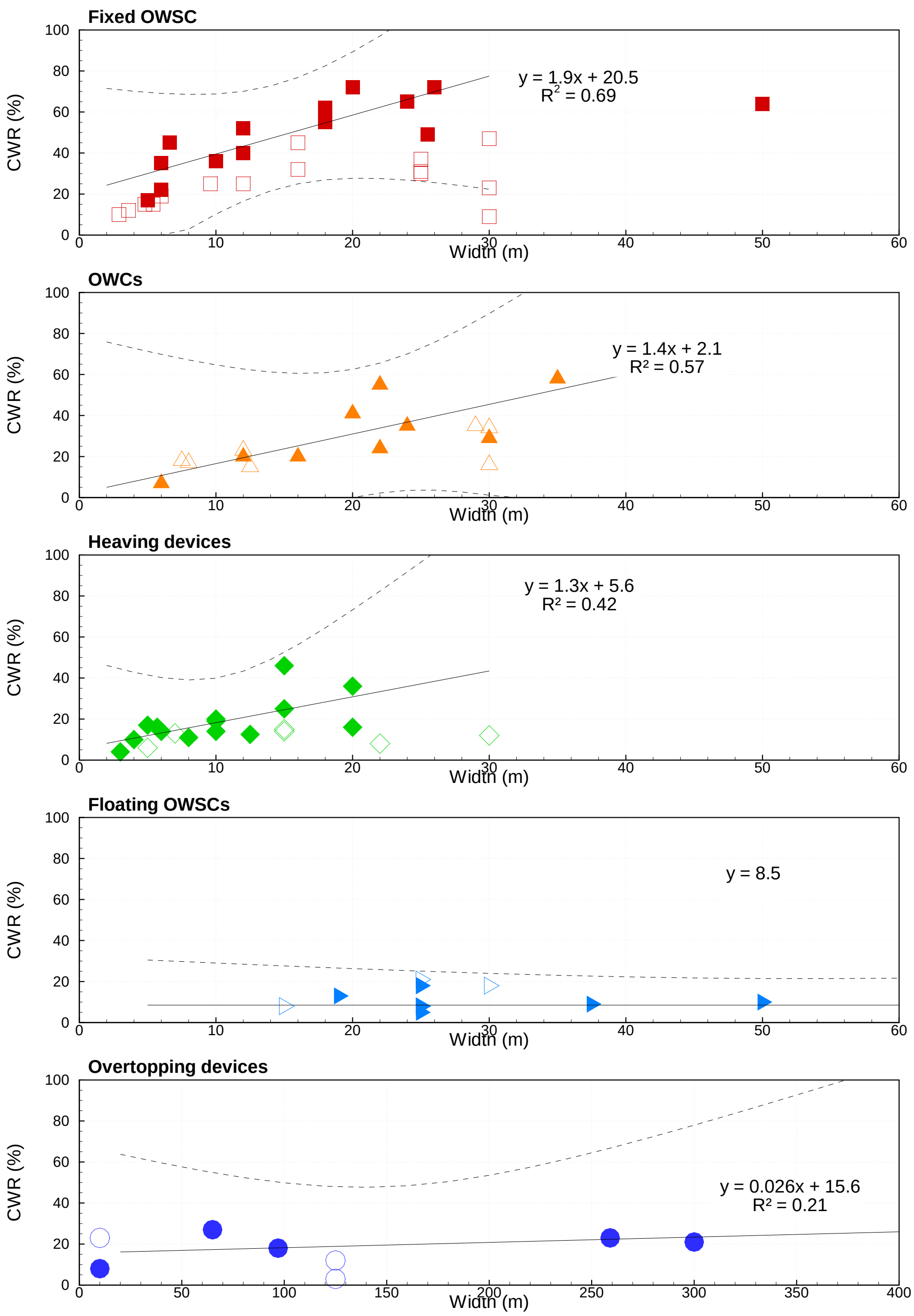

Figure 17: Data points, best fit equations and 95 % confidence interval for each category of WECs. For each category, empty symbols are for devices which are variants of the archetypal realization.

Conversely, the results from the statistical analysis (table 11) may be used to estimate the typical power performance for a given category of WEC, a characteristic dimension B and a for given mean wave resource J using:

$$P = \tilde{\eta}_1 B J \quad (5)$$

This may be useful in the early stages of WEC design, in order to check whether power performance of a particular WEC is in the range of performance figures available in the literature. It may help in detecting mistakes in the early stage of modelling, for instance, and may also be used in technico-economical prospective studies in order to estimate the wave energy potential of typical WEC technologies. However, it should not be used to assess the actual performance of a given WEC as it may differ significantly from the typical power performance of WECs of the considered category.

5. Conclusion

In this paper, available information from the literature relating to hydrodynamic power performance of WECs has been reviewed. A database was established that contains information on the WEC category (OWCs, overtopping devices, heaving devices, fixed OWSCs, floating OWSCs), its CWR, its characteristic dimension, the wave resource, the methodology that was used to derive the performance, and the reference for the information.

Analysis of this database indicated that the least efficient categories of WECs, in terms of absorbing wave energy, are floating OWSCs and overtopping devices, the most efficient are fixed OWSCs, with heaving devices and OWCs in the middle of the efficiency range. It is important to note that here, efficiency relates to hydrodynamic power performance (energy absorption) and not economical performance (cost of energy). Efficiency in the PTO system and the power conversion chain, as well as fabrication and operation costs, may be such that the most efficient device hydrodynamically speaking can be the least efficient device from perspective of cost of energy.

Statistical analysis was performed and statistical relationships were derived relating CWR to the characteristic dimension of WECs and the WEC category. It must be noted that uncertainties are large in the statistical results, as the number of measurements is rather small. However, it is believed that this statistical work may prove to be useful both in high level prospective studies and in detecting mistakes in the early stages of modeling.

It was observed that hydrodynamic performance varies significantly depending on the WEC category. In order to further investigate the underlying reasons for this, future work may compare capture width as a function of angular frequency for typical examples of the categories. Finally, WECs not belonging to one of the five categories listed above were not considered in this study because they are relatively new concepts and would constitute a category of their own. When more information becomes available for these new technologies, it may be interesting to compare their hydrodynamic performance with those of the categories considered in this paper.

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