Chapter 2
The Wave Energy Sector

Jens Peter Kofoed

2.1 Introduction

When entering the field of wave energy utilization it is relevant to ask—why is it important to start utilizing this resource? The reasons for this are shared with other renewable energy sources, such as hydro, wind, solar, biomass and other ocean energy forms such as tidal, currents, thermal and salinity driven systems. The key issues that the use of renewable energy sources can help to overcome includes environmental problems, depletion of the fossil fuels, security of supply and job creation.

The environmental problems relates to both local effects such as pollution but also the production of CO_2, which is related to energy production using fossil fuels, with the now well established negative effects on climate change as a consequence [1].

The depletion of fossil fuels was already highlighted in publications in the 1950s [2] and it is well established that the fossil fuels are finite and that the time horizon before they are depleted are counted in 10'ths, maybe 100'ths, of years. Thus, it is also obvious that the current level of energy consumption, which is by far majority based on fossil fuels, cannot continue unless alternative sources are developed. And here the renewable energy sources are the most obvious answers, as these resources will be available as long as the sun is shining.

But even still while there currently are reasonable amounts of fossil fuels available, the uneven distribution of the resource around the globe is giving rise to conflicts. It can only be expected that this tendency will be worsened as the fossil

J.P. Kofoed (✉)
Department of Civil Engineering, Wave Energy Research Group, Aalborg University, Thomas Manns Vej 23, 9220 Aalborg Ø, Denmark
e-mail: jpk@civil.aau.dk

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resources are getting more and more depleted. Thus, for most nations it is of great interest to decrease their dependency on fuel supply from other countries to maintain their sovereignty and political stability. As an answer to that renewable energy sources are very diverse and to a much larger extent scattered and well distributed around the globe, when looking at the renewable energy resource as a whole. Locally, large variations are present in which kind of renewable energies it is relevant to utilize. This also means that there is a need to develop a broad portfolio of renewable energy technologies to have sufficient 'tools in the toolbox' to fit the local needs.

In the current market, energy from the less mature technologies utilizing renewable energy sources are generally not cost competitive, but relies on political support. However, it can be expected that this situation will turn in the near future due to both the expected (and experienced) increase in cost of fossil fuels and the reduction of cost of the technologies utilizing renewable energy sources, due to further R&D and economics of scale.

In Denmark, as an example, it is a political goal to make the country independent of fossil fuels by year 2050. In September 2010 the Danish Commission on Climate Change Policy presented its suggestions as to how Denmark in the future can phase out fossil fuels [3]. The Commission's work had to reflect the ambition of the European Union that developed countries should collectively reduce their emissions of greenhouse gases by 60–80 % by 2050.

The task of the Commission was to present proposals for new proactive instruments for an energy and climate change policy with global and market-based perspectives that contribute to cost-effective attainment of the long-term vision. The Commission also had to assess new fields of technology and the potential for the market-based development of these technologies with the aim of implementing the long-term vision and assess the extent to which effective implementation requires internationally coordinated cooperation.

The analysis carried out by the Commission substantiates that a conversion of the energy system to be 100 % independent of the fossil fuels in 2050 is a realistic goal. Costs to society of such a conversion will only be modest.

To realize this goal a number of initiatives and technologies needs to be deployed. The key elements are; more efficient use of energy and the energy has to come from renewable sources. To get an impression of what is suggested refer to Fig. 2.1. A major part of the supply of electricity is expected to come from wind (60–80 % compared to 20 % today), but as illustrated in Fig. 2.1, also wave energy is foreseen as a technology contributing to the future energy mix. In other countries the wave energy is expected to a take a more central role—this is tightly linked to the available resource. As illustrated later in this chapter, the wave power level on the European Atlantic west coasts is up to 5 times greater than in the Danish part of the North Sea.

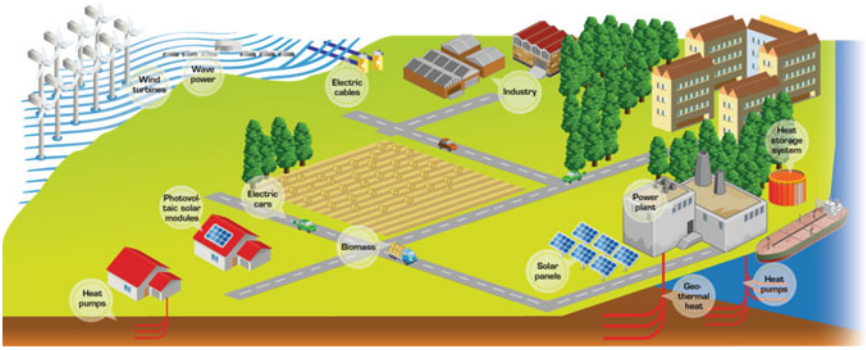

Fig. 2.1 An energy system without fossil fuels [22]

Compared to fossil fuel based energy production technologies most renewable energy investments are spent on materials and workmanship to build and maintain the facilities, rather than on fuel, which for renewable energy sources are for free. Renewable energy investments are to a much larger extent spent within the nation and often in the same local area (as a large share of the cost is going to operation and maintenance of the facilities) where the produced energy is consumed. This means the investment to a large intent stays in the neighbourhood where it create jobs and fuel the local economies, rather than going to regions far away. On the other hand, there are also opportunities for export for the nations who are successful in developing commercially viable renewable energy technologies. This has been experienced extensively in Denmark in where wind turbines are now one of the most important export articles.

When talking about utilization of wave energy for electricity production the current state is that the technologies are not yet mature. A number of full scale demonstration projects exists (examples hereof are given later in this chapter), but these are generally still in the R&D phase and the cost of the produced energy from these installations are multiple times greater than the target (market) level. However, efforts to reduce costs through optimization of structures, operation, control etc. as well as economics of scale are expected to be able to bring the cost of energy down to a level which at least is comparable with other more mature renewable energy technologies (such as offshore wind). It is in this context the current publication should be seen and is contributing to the advance of the field of wave energy utilization.

2.2 Potential of Wave Energy

When considering wave energy as a source for electricity production it relevant and interesting to look at the estimates of how large the potential for utilization is. Ocean waves including swells (waves generated by distant weather systems) are derived from solar energy, through wind, which when blowing over the ocean surface generates the waves. The waves travel over great distances with very little energy loss, as long as the waves are in deep water conditions. The types of ocean surface waves considered when taking about wave energy utilization are further discussed in Chap. 3. Here it is just noted that when addressing utilization of ocean waves what is meant is the wind generated waves (and possibly swells, depending on the specific device characteristics). Thus, the scope is limited to looking at ocean surface waves with periods in the range of 0.5–30 s. Besides tides, the remaining wave types hold in practice no potential for utilization. The utilization of tides for energy production is termed tidal energy and is not addressed further in this book.

When considering sea states (characterized by statistical wave parameters covering e.g. periods of $\sim$1000 waves) these are steadier than the wind field which generates the waves. The wave energy flux (power level) exhibits significant variation in time and space. It can range from a few W/m up to MW/m in extreme (stormy) conditions. The wave power level also exhibits a significant seasonal variation (1:5 in Danish waters), as well as year-to-year variation (±50 % in Danish waters) [4].

Early estimations of the global available wave power indicates a total potential of 2.7 (−70) TW [5]. [6] present a more detailed an updated study of the world wide wave energy potential, illustrated in Figs. 2.2 and 2.3 broken down into regions of the world.

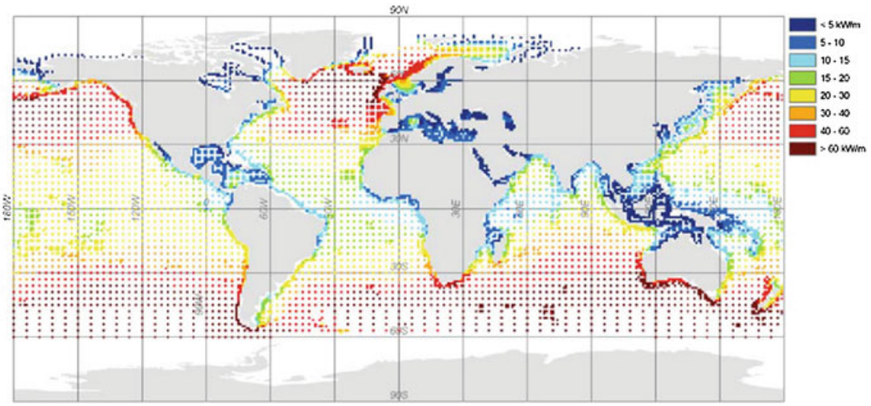

Fig. 2.2 Annual global gross theoretical wave power for all WorldWaves grid points worldwide [6]

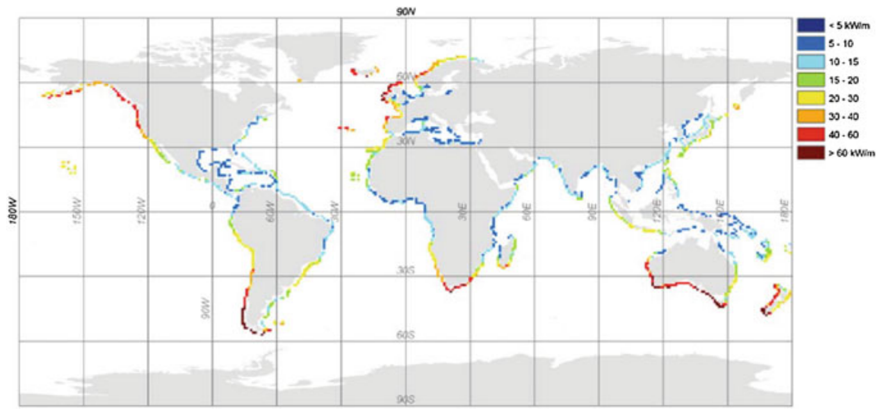

Fig. 2.3 Annual net theoretical coastal power worldwide (excluding contributions where $P \leq 5$ kW/m and potentially ice covered areas) [6]

The global gross theoretical resource is estimated at about 3.7 TW, 3.5 TW is the resource computed excluding areas with a benign wave climate (areas with less than 5 kW/m) and the net resource (where also areas with potential ice cover is excluded) is about 3 TW; the total reduction from gross to net resource is then about 20 %. In Europe there is a decrease of 25 % from gross to net resource, mostly a result of ice coverage, the gross and net values being 381 and 286 GW, respectively. To put these numbers into context note that the total world consumption in 2008 was 142.300 TWh [7] corresponding to an average power of 16.2 TW. In terms of electricity consumption the corresponding numbers are 20261 TWh and 2.3 TW [8]. Thus, the total wave energy resource exceeds by far the global consumption of electricity.

In many regions of the world more local studies of the wave energy resource have been performed, see e.g. [9]. Here, not only the gross theoretical resource is estimated for the US, but also the total recoverable resource (under specific assumptions) is estimated to be 44 % of the gross theoretical resource. So, if it is assumed that the numbers for the US can be applied world-wide it is reasonable to expect that the total recoverable global wave energy resource is approx. 2/3's of the global electricity consumption.

For Europe it is suggested in [10] that a total of 100 GW install capacity of ocean energy (note—this includes also a contribution from tidal energy), generating 260 TWh/y, by 2050 is a realistic target. For comparison it can be noted that in 2005 83 TWh was produced by 40 GW of installed wind turbine capacity in Europe, and by 2030 these numbers are expected to reach 965 TWh and 300 GW [11]. In other words, wave energy has a significant potential for Europe, but will most likely remain minor compared to the wind industry. However, as the renewable energy resources cover a larger and larger share of the electricity consumption, the timing and predictability of the power production becomes increasingly important, and in this respect will a combination of wind and wave (in combination with the other renewable energy sources) be far more beneficial compared to wind alone.

For Denmark, a mapping of the wave energy potential in the Danish part of the North Sea is available from [4]. In here, the gross theoretical resource for this area is estimated to be 3.4 GW, which can be compared to the annual electricity consumption in Denmark [12] of 4.4 GW, i.e. 85 % hereof. In [13] a rough estimation of how this resource could be utilized is given, showing a production of 30 % of the electricity consumption is technically feasible (or 35 % of the gross theoretical resource).

So, to sum up—the potential of wave energy utilization for supplying a significant part of world electricity needs is there. Next question is then regarding which technologies can be used for this purpose? A more detailed description of the wave energy resource is given in the dedicated Chap. 3 entitled: Wave energy resource.

2.3 Wave Energy Converters

2.3.1 History

The development of wave energy converters (WEC's) goes far back in time—the first attempts are recorded to have taken place in the 1800s, see Fig. 2.4 and [14]. Actually, the first patent for a wave energy converter dates back the year 1799. In

Fig. 2.4 Postcard from a "wave motor" experiment off the coast of Santa Cruz from 1898 [23]

modern time it was not until the energy crisis in the beginning of the 1970s that the field had renewed interest, greatly boosted by an article by Prof. Stephen Salter in the scientific journal Nature in 1974 [15]. However, in spite of very significant research efforts, not the least in the UK, activities were reduced again up through the 1980s and the beginning of the 1990s. By the end of the past millennium activities were picking up in speed again, and this now in a number of countries around the world, but with most efforts seen in the coastal European countries. Over the past decade UK has again put enormous efforts into development of marine renewable energies, including wave energy, and must today be seen as the world leader in the field.

2.3.2 Categorization of WEC's

The development of WEC's is characterized by the fact that there is a large number of different ideas and concepts for how to utilize the wave energy resource. The different concepts can be categorized in a number of different ways.

Often a basic categorization using the terms terminator, attenuator and point absorber is used [42]. *Terminators* are devices with large horizontal extensions parallel to the direction of wave propagation, while *attenuators* have large horizontal extensions orthogonal to the direction of wave propagation. In contrast *point absorbers* with extensions small compared to the predominant wavelength of the prevailing waves.

WEC's can also be categorized by their location—*onshore*, *near shore* and *offshore*. Onshore, or shore-mounted, devices are by nature terminators, and rigidly connected to land. Typical examples hereof are oscillating waver columns and overtopping devices, see further explanation below. Near shore devices are situated at water depths where the available waves are influenced by the water depth, and devices deployed in this region will often be bottom mounted. And thus, at last, devices placed offshore will generally be floating and have access to the waves unaltered by the presence of the seabed.

Classification of WEC's is also seen by their main working principles [44]. The European Marine Energy Center at the Orkney Islands is using 8 main types, plus one ('other'—in acceptance of the fact that some WEC's cannot be put into the existing boxes).

However, in the following, the approach to categorization used by IEA—Ocean Energy Systems [16] will be used. This approach is illustrated in Fig. 2.5.

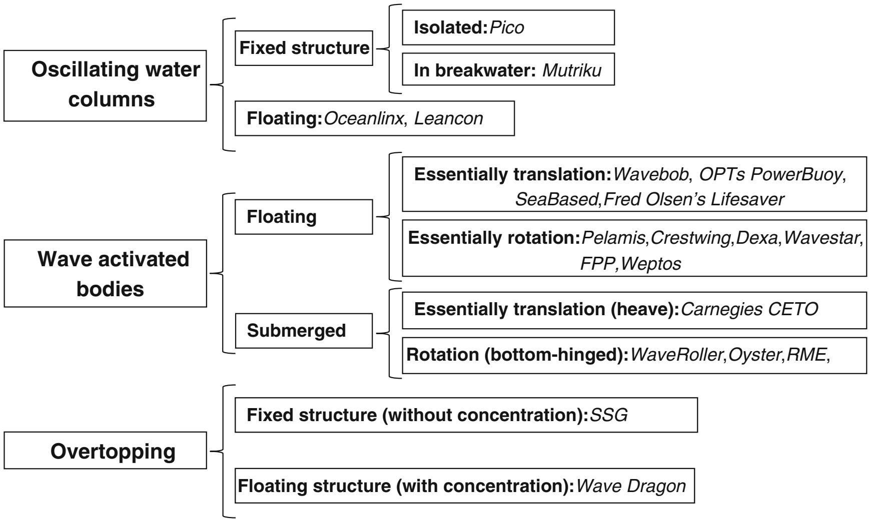

Fig. 2.5 Categorization of wave energy technologies following IEA – Ocean Energy Systems [16]. Technologies mentioned in the various categories are the ones illustrated in the following figures

Here, all WEC's consisting of oscillating bodies are put into one category. This category is termed Wave Activated Bodies (WAB's).

In an attempt to detail the categorization of WEC's a level further, guidelines have been provided by the EU-FP7 funded EquiMar project on how to categorize WEC's by subsystems [17]. The WEC is in this case broken into the following subsystems, which can then be individually categorized:

- Primary energy extraction
- Power take-off/control system
- Reaction system

The concept for detailed categorization and breakdown of a WEC is developed further by DNV-GL in [18], which provides a generic system breakdown useful as base of a generic risk ranking and failure mode analysis.

2.3.3 Examples of Various WEC Types

In the following a wide range of examples of WECs, however only a fraction of the technologies that are currently being developed around the world, are presented, here categorized according to the categories defined by IEA—Ocean Energy Systems (following Fig. 2.5).

2.3.3.1 Oscillating Water Column

There is a number of shore-based (fixed) oscillating water columns (OWC) WECs that has been operating, on Islay in Scotland (operated by *WaveGen*), the Pico plant on the Azores in Portugal (Fig. 2.7), at the port Mutriku breakwater in Spain (Fig. 2.6), Sagata port Japan and OceanLinx Australia (Fig. 2.7). The unidirectional rotation of the air turbine (the Wells type) is a simple way to rectify the bidirectional flow and thereby convert the oscillating power from waves, due to the fact that the need for check-valves can be omitted and the structure thus constructed with less moving parts. Voith Hydro WaveGen Limited has been developing this type of turbines.

Fig. 2.6 Mutriku Oscillating Water Column breakwater, equipped with 16 WaveGen Wells turbines, total capacity of 300 kW [24]

Fig. 2.7 The Pico OWC, schematics (*top*, *left*) and in action (*top*, *right*) [25], OceanLynx, schematics (*lower*, *left*), and in real life (*lower*, *right*) [26]

The *LeanCon* WEC is floating and also based on the concept of oscillating water columns (Fig. 2.8). It is a large structure covering more than one wave length and it consists of a large number of OWC chambers. This entails that the resulting vertical force on the WEC is limited. The downward forces from the negative pressure on parts of the WEC prevent it from floating up on the top of the waves and due to this the device can have a low weight (constructed from high strength fiber reinforced material). Before the air flow reaches the power take off system (PTO) the air flow is rectified by the non-return valves. Thus, LeanCon uses uni-directional air turbine, while most other OWC use Wells turbines.

Fig. 2.8 Leancon 1:40 scale model in wave basin (*top*, *left*), 1:10 prototype for testing in Nissum Bredning, Denmark, under construction (*top*, *right*) and after deployment (*middle* and *bottom*). Courtesy of LeanCon

2.3.3.2 Wave Activated Bodies

The category of wave activated bodies (WABs) encompasses a very large field of WEC concepts. In this section a number of examples are given to give an impression of the plurality, but it cannot be considered complete as the number of concepts in this category can be counted in hundreds.

The *Pelamis* WEC is a floating device, made up of five tube sections linked by universal joints which allow flexing in two directions (Fig. 2.9). The WEC floats semi-submerged on the surface of the water and inherently faces into the direction of the waves, kept in place by a mooring system. As waves pass down the length of the machine and the sections bend in the water, the movement is converted into electricity via hydraulic power take-off systems housed inside each joint of the machine tubes, and power is transmitted to shore using standard subsea cables and equipment [19].

Fig. 2.9 E.ON P2 Pelamis operating in Orkney July 2011 [27]

Like Pelamis, the *Crestwing* is a moored device utilizing the relative motion between wave activated bodies (Fig. 2.10). While Pelamis is harvesting the energy from 2 degrees of freedom (DOF) in a total of 4 joints, Crestwing is just using a single DOF for power production. The hinged rafts of the Crestwing are closed box structures. And the PTO of the Crestwing is a mechanical system using a ratchet mechanism and a fly wheel for converting the oscillatory motion between the rafts into a rotating motion on an axle, which can be fed into a gear and generator system. Other concepts have been tested using relative rotation between floating

Fig. 2.10 Crestwing, at a scale of 1:5, tested near Frederikshavn during autumn 2011 [28]

Fig. 2.11 Picture of Dexawave at DanWEC [29]

bodies includes *Dexa* (Fig. 2.11), *Martifer*, *MacCabe Wave Pump* and *Cockerell's Raft*.

Another group of floating WABs includes translating (often heaving) bodies. This includes devices *Ocean Power Technologies (OPT)* (Fig. 2.12), which is one among a number of technologies utilizing a point absorber. The OPT PowerBuoy is using a reference plate as point of reference for the PTO. OPT has used different solutions for PTO, including oil hydraulics. OPT is working on a range of deployment projects, and have conducted sea trials using both a 40 kW and 150 kW version of their technology. Other devices using similar approaches include *Wavebob* (using a submerged volume rather than a damping plate for reference) (Fig. 2.13) and *SeaBased* (using a fixed reference point at the seabed, where also the PTO, a linear generator, is placed (Fig. 2.14).

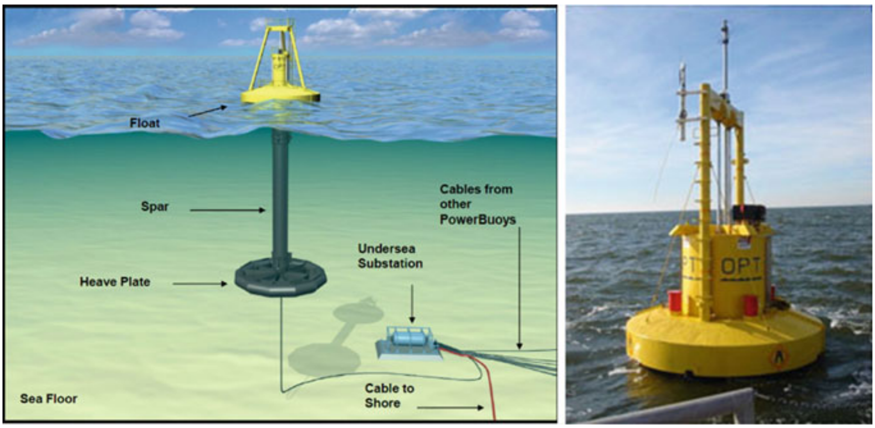

Fig. 2.12 OPTs PowerBuoy PB40. A slack moored pointer absorber with heave plate [30]

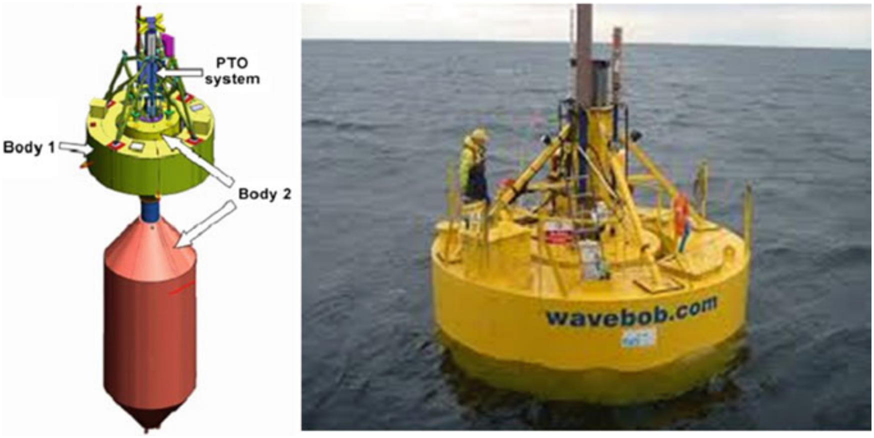

Fig. 2.13 Wavebob. A slack moored pointer absorber with submerged reference volume [31]

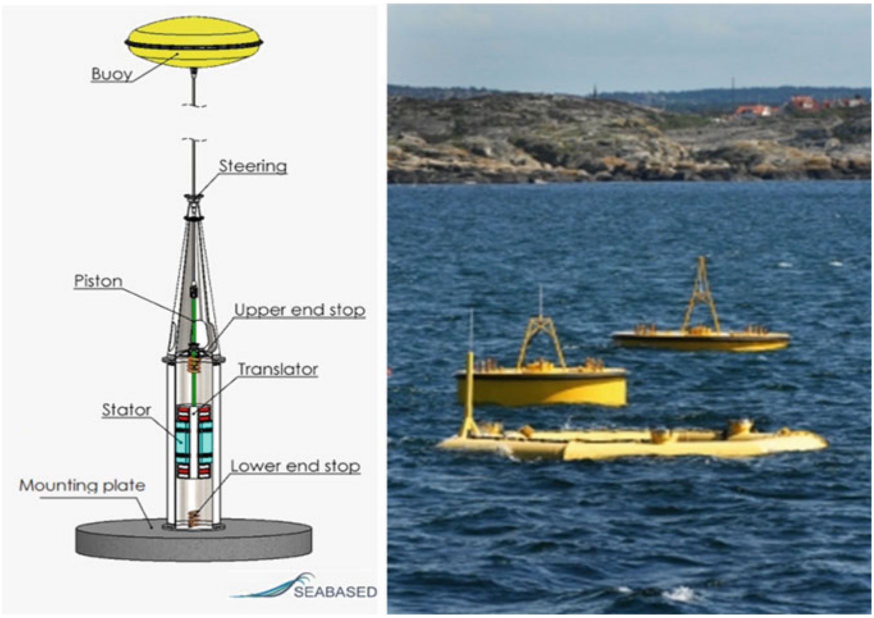

Fig. 2.14 SeaBased. A point absorber with a directly driven linear generator placed at the sea bottom [32]

Other types of point absorbers also exists, such as Fred Olsens Lifesaver, which not only utilizes the heave (translation) but also the pitch and roll (rotation), as it consists of a torus connect to the seabed through winches with integrated PTOs (Fig. 2.15).

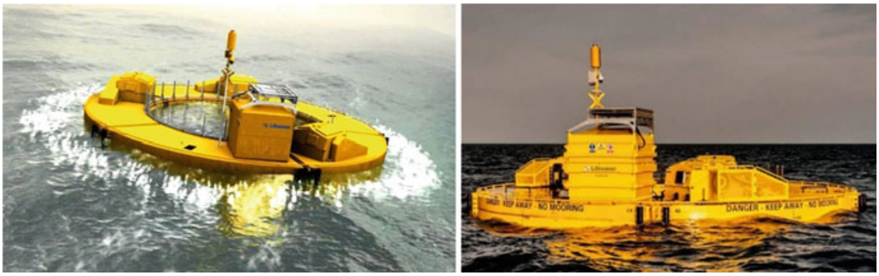

Fig. 2.15 Fred Olsen's Lifesaver buoy, illustration (*left*) and deployed at Falmouth test site (FabTest) (*right*). Courtesy of Fred Olsen

As an example of a submerged WAB Carnegies *CETO* buoy can be mentioned. In the CETO device the buoy itself is completely submerged and kept in place by a tether fixed at the seabed and with a hydraulic pump based PTO in line (Fig. 2.16).

Fig. 2.16 Carnegies CETO. A submerged tether moored point absorber [33]

Besides the above, another group of fixed WABs, specifically submerged flaps hinged at the seabed, can be mentioned. This type includes *Oyster*, developed by Aquamarine, which was announced in 2001 by Professor Trevor Whittaker's team at Queens University in Belfast (Fig. 2.17). The flap is moved back and forth by the waves, and power is taken out through hydraulic pumps mounted between the flap and the structure pinned to the seabed. The latest generation Oyster 800 has an installed capacity of 800 kW. It has a width 26 m and height of 12 m was installed in a water depth of 13 m approx. 500 m from the coast of Orkney at EMEC.

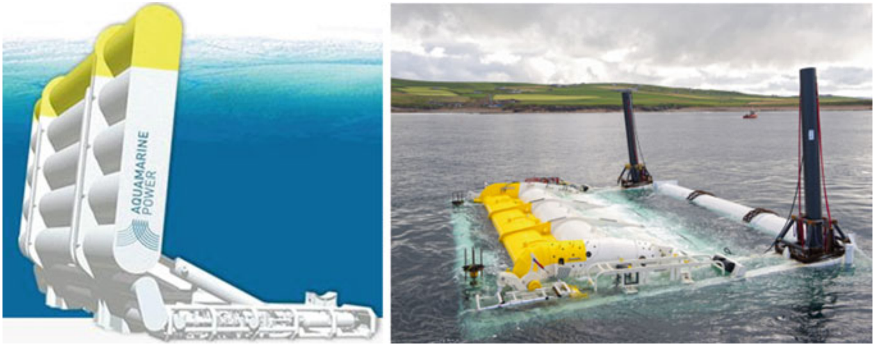

Fig. 2.17 Installation of the Oyster 800 submerged flap WEC at the European Marine Energy Centre in Orkney, Scotland [34]

Other relevant WECs utilizing same operating principles includes *Waveroller* (Fig. 2.18), *Resolute Marine Energy* (Fig. 2.19) and *Langlee* (Fig. 2.20). However, the latter is not fixed to the seabed, but a structure with two flaps attached to a floating reference frame.

Fig. 2.18 Waveroller WEC prototype, before submerged to seabed [35]

Fig. 2.19 Resolute Marine Energy (RME) WEC prototype [36]

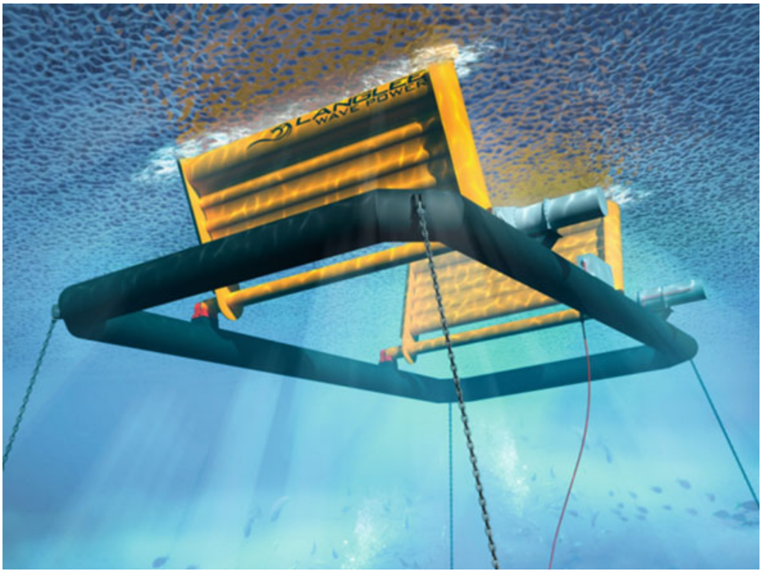

Fig. 2.20 Artist impression of the Langlee WEC. A floating submerged flap WEC [37]

In addition to the above mentioned WECs in the WAB category, also a number of devices exist where multiple bodies are combined into one larger structure. An example here is the *Wavestar* device, which consists of two rows of round floats—point absorbers—attached to a bridge structure, fixed to the sea bed by the use of steel piles, which are cast into concrete foundations (Fig. 2.21). All moving parts are therefore above normal seawater level. The device is installed with the structural bridge supporting the floats directed towards the dominant wave direction. When the wave passes, the floats move up and down driven by the passing waves, thereby pumping hydraulic fluid into a common hydraulic manifold system which produces a flow of high pressure oil into a hydraulic motor that directly drives an electric generator. A prototype with a total of two floaters (diameter of 5 m) has been undergoing sea trials at DanWEC, Hanstholm, Denmark.

Fig. 2.21 Wavestar prototype with two floaters, at DanWEC, Hanstholm, Denmark (*left*) and concept for full scale deployment, artists impression (*right*). Courtesy of Wavestar [38]

Another multi-body device is the Floating Power Plant (Fig. 2.22). This device is a moored structure utilizing multiple WABs aligned parallel to the wave crests. Thus, the operating principle resembles to some extent the Wavestar, except the reference structure here is floating and not bottom mounted. Furthermore, the floating structure is used as a floating foundation for wind turbines. Floating Power Plant has carried out sea trials at a benign site with a reduced scaled prototype, and is currently preparing its first full scale prototype deployment.

Fig. 2.22 Floating Power Plant, prototype deployed at Vindeby off-shore wind turbine farm, off the coast of Lolland in Denmark (*top*) and illustration of latest design (*bottom*). Courtesy of Floating Power Plant

The *Weptos* WEC is another floating and slack-moored structure, composed of two symmetrical frames ("legs") that support a multitude (20) of identical rotors (Fig. 2.23). The shape of these rotors is based on the shape of Salter's duck WEC (invented and intensively developed since 1974 [15]). All rotors on one leg are connected to the same frame are driving a common axle. Each axle is connected to an independent PTO. The torque, resulting from the pivoting motion of the rotors around the axle, is transmitted through one-way bearings on the up- and down-stroke motion of the rotor. The angle between the two main legs is adaptable. This allows the device to adapt its configuration relative to the wave conditions, increasing its width relative to the incoming wave front in operating wave conditions and reducing its interaction with excessive wave power in extreme wave conditions.

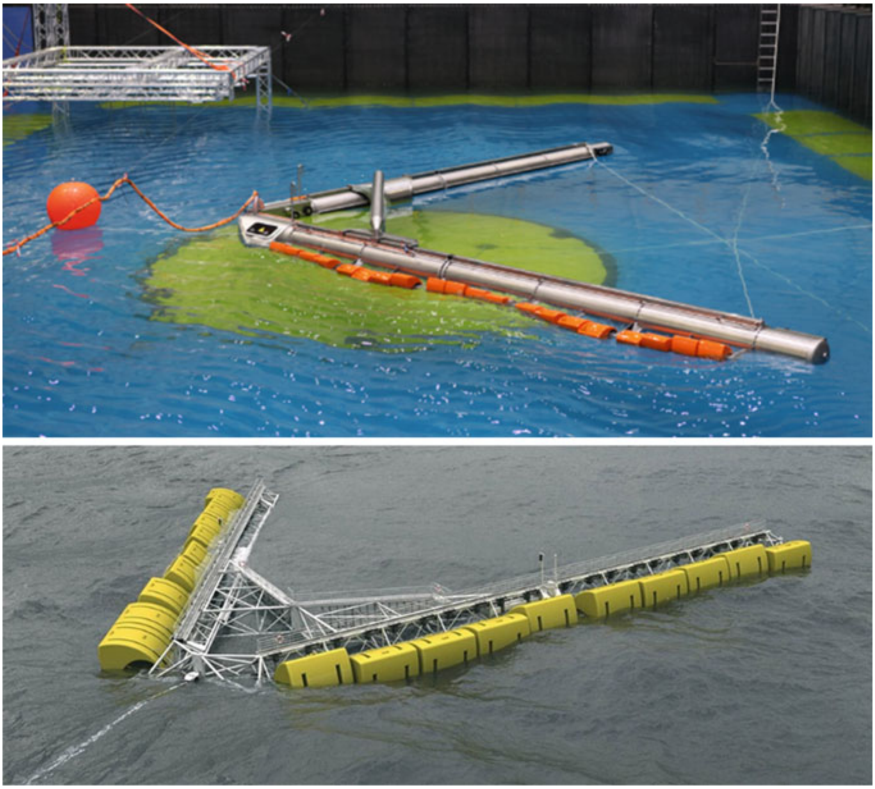

Fig. 2.23 A fully functional WEPTOS model undergoing testing at CCOB, IH Cantabria, Spain (Sept. 2011) (*top*) and artist impression of the full scale Weptos WEC (*bottom*). Courtesy of Weptos [39]

2.3.3.3 Overtopping Devices

The *Wave Dragon* is a slack moored WEC utilizing the overtopping principle (Fig. 2.24). The structure consists of a floating platform with an integrated reservoir and a ramp. The waves overtops the ramp and enters the reservoir, were the water is temporarily stored before it is led back to the sea via hydro turbines generating power to the grid, and thereby utilizing the obtained head in the reservoir. Furthermore, the platform is equipped with two reflectors focusing the incoming waves towards the ramp, which thereby enhance the power production capability.

Other overtopping based approaches do also exist, including the *SSG*, which is a fixed structure acting as a combination of a WEC and a breakwater (Fig. 2.25). In order to still being able to harvest the wave power with good efficiency, while not having the option of adjusting the ramp height through the floating level, SSG consists of multiple reservoirs with different heights. However, simpler approaches with just a single reservoir integrated into (existing) breakwaters are also being explored.

2.3.4 The Development of WECs

As seen above a large variety of WECs exists, and more are still appearing. EquiMar (an EU FP7 funded research project [20]), along with others, has promoted the use of a staged development approach to the development of WEC's, and

Fig. 2.24 Wave Dragon 1:4.5 scale grid connected prototype tested in Nissum Bredning, Denmark

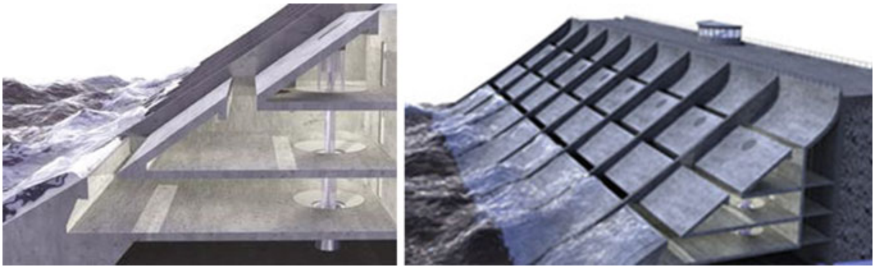

Fig. 2.25 Conceptual drawings of the SSG [40]

thus, the stage of development can also be used for characterization of the WEC's. EquiMar uses 5 stages to describe the development of a WEC from idea to commercial product. These 5 stages are illustrated in Fig. 2.26.

Each stage should provide specific valuable information to inventor and investors, before going to the next step, and hereby avoid spending too many resources before having a reliable estimate on the concepts potential.

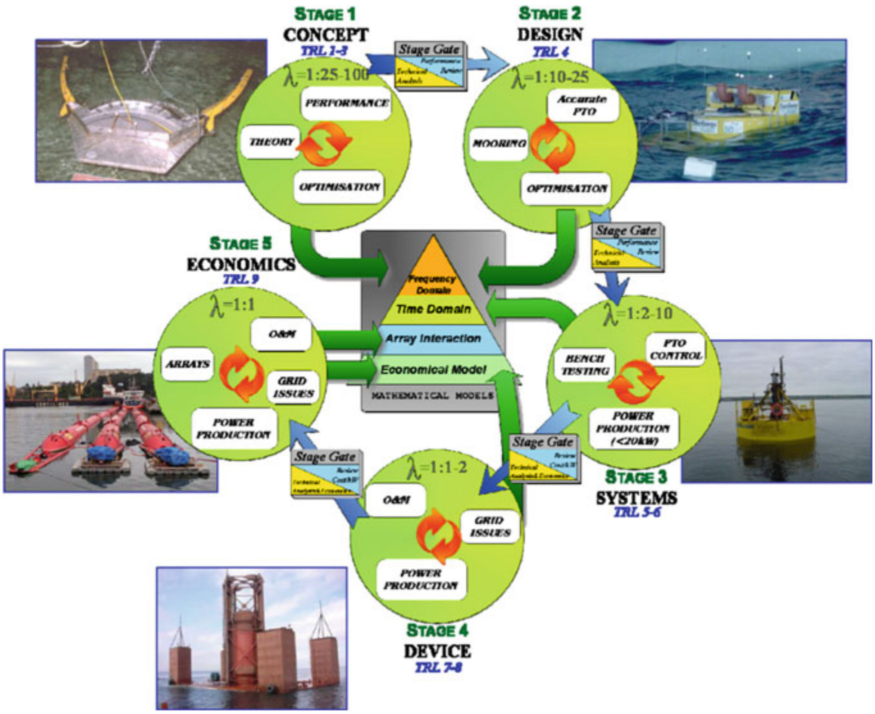

Fig. 2.26 The 5 development stages used for description of the development of a WEC from idea to commercial product used by the EquiMar project. Courtesy of EquiMar [20]

This topic will extensively be addressed in the corresponding Chap. 4 entitled: Techno-economic development of WECs.

As seen from the above examples of WECs and the staged development approach, an important element of the development is the initial real sea testing of the WEC prototype, which paramount prior to commercial introduction to the market. This has called establishment of test sites in real sea, which is the topic for the next section.

2.4 Test Sites

A number of test sites for testing and demonstration of WEC prototypes at real sea have been established throughout Europe over the past couple of decades. One of the first, and most developed, is the European Marine Energy Center (EMEC), established in 2003 at the Orkney Islands, which is providing open-sea testing facilities, as well consultancy and research services.

In Fig. 2.27 this and many other test sites in Europe are pointed out.

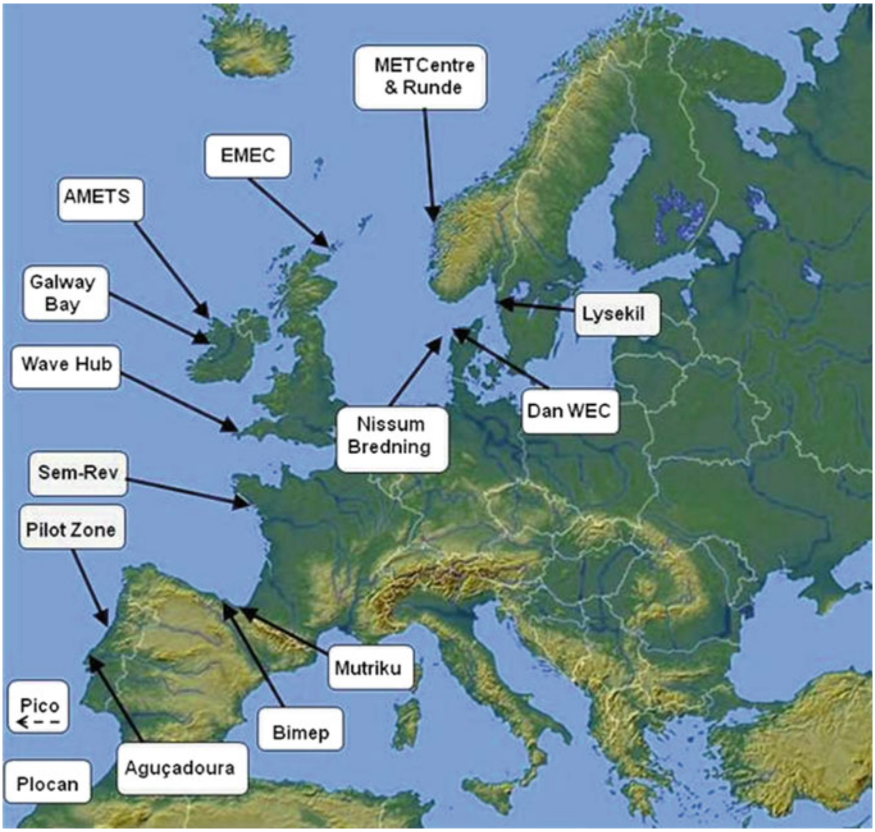

Fig. 2.27 Wave energy test sites throughout Europe [41]

In [21] details, including wave data and more, are given for a number of the illustrated test sites. From the detailed wave data given here, the graphs in Figs. 2.28 and 2.29 have been generated.

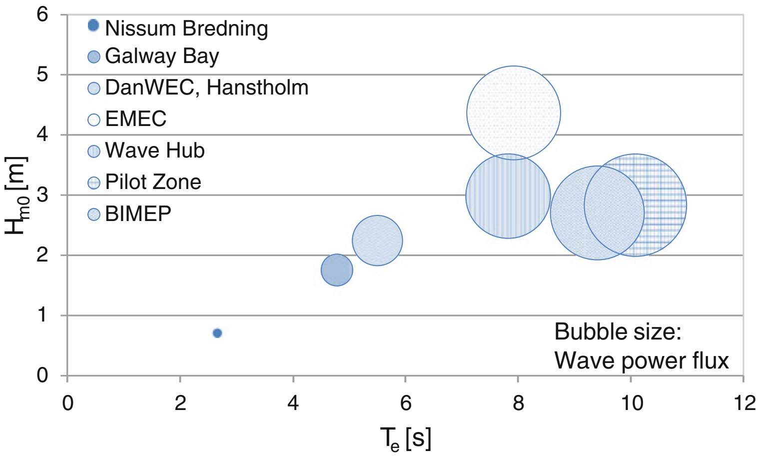

Fig. 2.28 Characteristic power production wave conditions (significant wave height and energy period) at selected European test sites (Weight averaged with contribution to mean wave power flux)

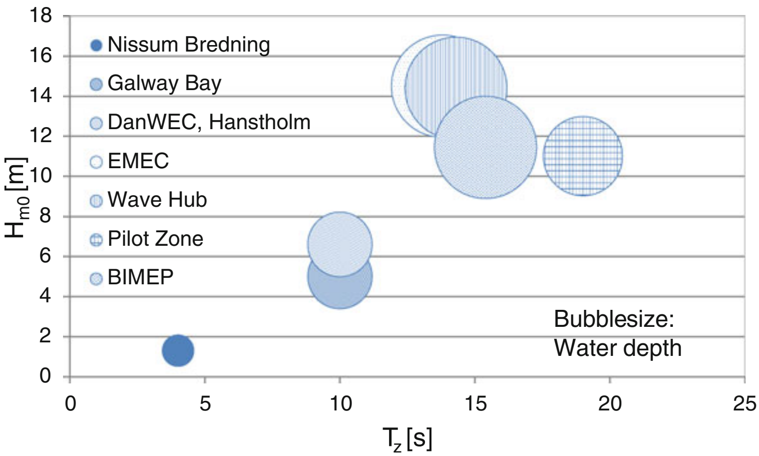

Fig. 2.29 Extreme wave conditions (significant wave height and average period) at selected European test sites

From the figures it is clear to see that the test sites cover a rather wide range of sea states, in production as well as extreme conditions. This corresponds well with the need for real sea test sites from pre-commercial scales to sites with conditions corresponding to the harsh conditions the WECs will be facing at fully commercial sizes.

It is interesting to note that especially the BIMEP and the Pilot Zone sites are dominated by significantly longer waves in production conditions. This has to be carefully considered when designing the WEC prototypes for these locations, as this for most types of WECs means that these sites primarily are well suited for very large devices, as tuning the WEC to larger wave periods inevitably leads to a larger structure.

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