



## REVIEW ARTICLE

# A review of the technologies for wave energy extraction

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## Abstract

The main objective of this article is to provide a comprehensive picture of existing wave technologies being used for wave energy extraction. The overview will explain their potential and also the challenges wave technologies face. The article will also briefly discuss the benefits of combined offshore wind-wave projects, also known as hybrids. Key factors and impacts on relevant existing wave technologies will be outlined, including capacity factor and capture width. Finally the levelized cost of energy (LCOE) targets for the most promising technologies will be discussed.

**Keywords:** wave power; wave energy converters; capacity factor; capture width; hybrid solutions

## Introduction

In order to reduce greenhouse gas emissions and to secure a sustainable future for all countries, it is clear that renewable energy sources will play a key role. According to the *Renewables 2016 Global Status Report* [1], globally, fossil fuel consumption is ~78.3% of the total share of energy consumption, followed by renewable energy sources with 19.2%. Traditional biomass accounts for 8.9%, while modern renewable energy has a percentage of 10.3%, dominated by solar and wind. The gap between fossil fuel consumption and the renewable market can be closed in the near future if we take into account recent progress from the renewable energy sector. Globally, the renewable energy sector between 2004 and 2013 (excluding hydropower) increased from 85 to ~560 GW. Leading the sector was the wind industry with growth from 48 to 318 GW, followed by the photovoltaic sector from 2.6 to 139 GW. The growth in the renewable sector was due to a number of factors including political support, financial incentives and reduction in the costs of technology making renewable energy cost competitive [2].

Marine energy technology is at an early stage of development, especially in the case of wave power. Wave power needs specific environmental conditions to be created. The energy is equally divided between: (i) the potential energy component, where the water is forced against gravity from the wave trough and crests and (ii) the kinetic energy component, that is, the water oscillating velocity [3]. To use this power it is important to design a structure that can efficiently capture and harvest the energy transmitted by the waves. A further key factor is that the structure must be able to survive the marine environment, in particular, storm events wherein the wave power significantly increases. One means to convert the wave energy into mechanical energy is by using a generator that is fixed (on the sea bottom or shoreline) with parts of this system in motion. During recent decades, floating systems were introduced that are capable of being deployed offshore. The systems can be designed and targeted to take advantage of both potential and kinetic energy, individually or at the same time [4].

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The potential of the Global Ocean's resources is significant when considering the combinations possible between large water surfaces and marine natural resource diversity. There are a wide variety of energy extraction options, including waves, tidal and ocean currents, ocean thermal energy, salinity gradients, marine biomass and submarine geothermal energy [5]. A successful example of using the marine environment is the offshore wind industry. The European wind market currently has 81 offshore grid-connected projects shared by 10 European countries capable of generating a total of 12.6 GW [6]. Under current trends, we estimate that by 2020 the total capacity will be close to 24.6 GW, based on statistics reported for 2016. Several technological developments have contributed to this prediction: the average offshore wind turbine is 4.8 MW; the first 8-MW turbine has been connected to the grid; the average size of a wind farm is 380 MW (+12% from 2015); the average water depth is 29 m; and the average distance to shore is 44 km. The offshore wind energy sector has continually expanded since 2000 with larger size wind farms, turbines and distances from shore. In 2015 almost €18bn was invested in transmission assets and new offshore wind projects [6, 7].

The wave energy sector could potentially equal and even exceed the offshore wind sector, if we take into account that waves are a concentrated form of wind energy capable of travelling large distances with minimal losses. There are two categories of waves: wind seas (waves generated locally) and swell (waves generated by distant winds). The swell wave is more important for the wave energy converter (WEC) industry as the energy density is more consistent. The worldwide potential of wave power is around 29500 TWh/yr, from which currently only a small fraction is efficiently extracted near ocean coastlines, islands or semi-enclosed basins defined by local 'hotspots' [8, 9]. In general, a hotspot is a site that reveals the best balance between wave energy potential and other relevant factors, such as distance to the shore, water depth or investment costs. In recent years, various onshore and offshore projects have been developed, including the Islay plant (Scotland) and the Pico Island plant (Portugal). The Islay project involved the construction and testing of the LIMPET (Land Installed Marine Power Energy Transmitter) system, which has a generating capacity of 500 kW. This unit was installed in 2000 on an island off the western coast of Scotland, and includes three water columns made from concrete and inclined horizontally at 40°. The water columns' motion is converted into electricity throughout two counter-rotating Wells turbines operating at 700–1500 rpm [10].

The Pico plant is located in the Azores, with an installed capacity of 400 kW and was built between 1995 and 1998, under the supervision of the Instituto Superior Técnico (IST), Lisbon. Various problems emerged during this time due to the plant configuration and equipment. In 2005 the project was redesigned, and in 2009 project developers reported a full operating time of 265 hours [11]. Most of the systems are still in the early stage of development

(small-scale systems) and only a few generators are being tested in marine environments (sea trials). These tests are to assess the efficiency of the systems in terms of electricity generation and survival issues.

Because there are no large-scale wave farms, it is difficult to predict the future of this industry, although opportunities are expanding as the technology evolves [12]. The successful development of wave technology in the European wave market could generate 188 GW (10%) of Europe's electricity needs by 2050. However, for this to happen would mean the successful development and operation of new wave generation systems planned for 2022–2040. Research and development (R&D) on current projects has provided knowledge on how to cut the costs for future wave technologies. Improvements in the next generation of wave technology could reduce the costs of power take-off (by 22%), installation (18%), operation and maintenance (17%), foundation and mooring (6%) or grid connection (5%) [13]. A promising option to cut costs is the combination of WECs with existing offshore wind parks by sharing the same infrastructure. This could assist in the acceleration and development of the wave industry in areas with moderate wave energy potential [14–18].

Since a renewable marine project is designed to be a sustainable project, it is important to understand its impact on the local marine ecosystem. In general, this seems to be beneficial for the fish population, since there will be exclusion zones prohibiting fishing around the generators. In addition, because the wave energy converters will work similar to a breakwater, they will calm the sea, thus providing a nesting area for local bird species [19].

## 1 Wave energy potential

The energy profile of a wave is directly related to the intensity and persistence of the wind speed, taking into account also the scale of the fetch area where the wind blows. From the energy aspect, the most attractive areas are found between 30–60° in both hemispheres, with the total theoretical energy potential around 32000 TWh/yr [5]. Over the last few decades numerous monitoring systems have become operational to better measure wave energy potential. The in situ instruments still remain the best source of information, but since they are operating only in a few locations it is impossible to provide a complete picture of the wave energy potential from a particular area. Another important source of measurements is by satellites orbiting on a predefined track, sometimes combining several missions into a multi-mission project, which assemble a homogeneous data set defined by a good temporal and spatial resolution [20, 21]. Note that the accuracy of the beam signal is influenced by the coastal and island contamination (presence of land), and as a result the data set may include missing values, which are gaps in the time series, usually denoted with NaN (not a number) [22, 23].

New, more powerful computers bring new opportunities to gather data for wave prediction. It is now possible to develop numerical models on global and regional scales. These include projects maintained by the European Center for Medium-Range Weather Forecasts (ECMWF) [24] and the US National Centers for Environmental Prediction (NCEP) [25] that are capable of providing data and information on a global scale. Recent research has highlighted that a more accurate description of wave conditions is generated from a wave model focused on a particular area in combination with data assimilation systems [26].

Fig. 1 illustrates the total wave power distribution (expressed in gigawatts) for various coastal environments based on the National Oceanic and Atmospheric Administration's WaveWatch III data [27]. Note that the index results are from the wave power density, which shows the amount of energy flux per meter of wave crest (kW/m). According to this data, sites located in North America have more significant resources compared to Europe, which is less attractive, although most of the WEC research comes from this region. According to these values, if we focus

on the regional scale we can see that the wave power is more consistent around Australia, followed by the USA and Chile, while Portugal and France show much lower values. A possible explanation for these results may be that, for this work, the entire coastal area was considered, which in the case of Australia or North America is much greater compared to other regions such as Portugal.

Fig. 2 depicts an assessment of the wave power density from various sites around the world. The results reported, according to the point position to the center of the targeted region (e.g. NW: Northwest; SE: Southeast), are indicated in terms of the total and winter time. As expected, the values reported during winter are more significant, where the total time values (from January to December) at some sites appear to be more consistent, such as in the Southwest Asia region.

## 2 Wave energy converters

Historically, the first WEC system was developed in France, with the first WEC patent granted in 1799. The forerunner

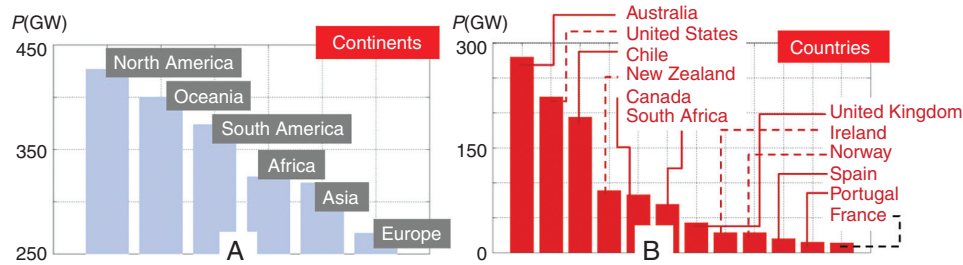


Fig. 1 Total wave power: annual means estimated for (a) continents and (b) countries. Results processed from Gunn and Stock-Williams [27]

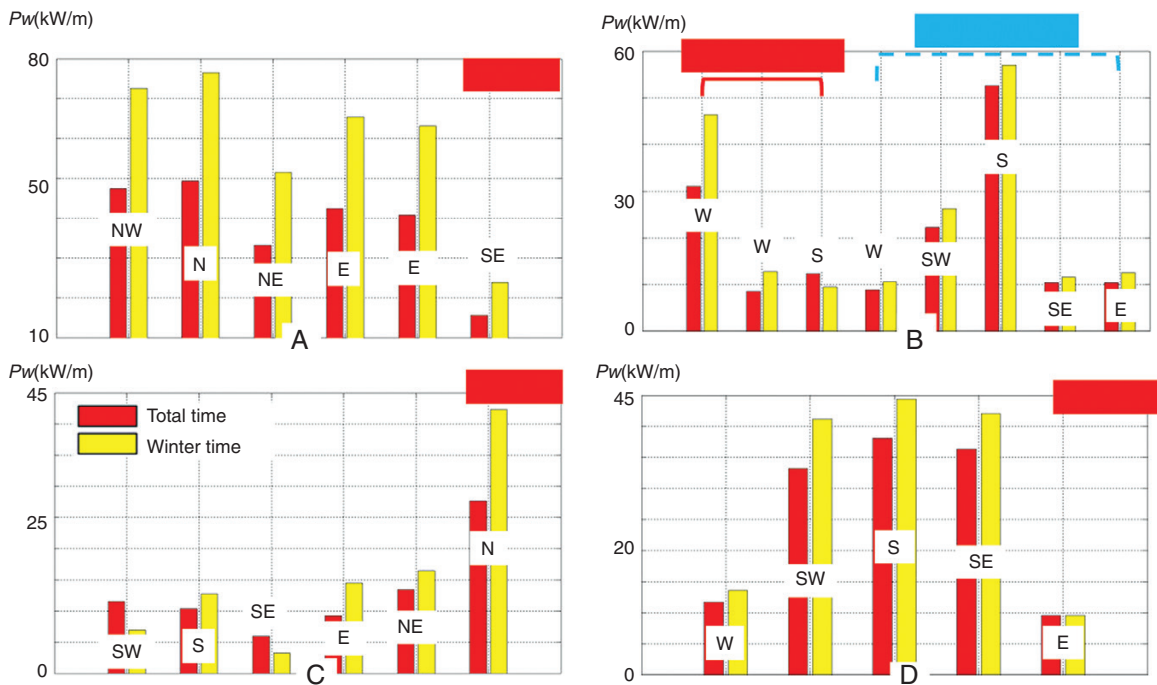


Fig. 2 Average wave power (in kW/m) reported on a global scale, corresponding to the 15-year time interval (2000–2014) of ECMWF data according to Rusu and Onea [28]

of modern wave energy systems was developed in Japan by Yoshio Masuda in 1940 with the first floating oscillating water column incorporated into a navigation buoy. Since then, more than 1000 patents have been issued, with each project being defined by a particular design and power take-off system (air, hydraulic, electrical, mechanical), which represent the mechanism absorbing the wave energy and transforming it into electricity [29, 30].

Fig. 3 illustrates the main types of WECs, according to their working principle or whether they are installed onshore, nearshore or offshore. In the onshore area the most common systems are based on an oscillating water column, where the air is trapped in a semi-submerged chamber and is compressed and decompressed to rotate a turbine and to generate electricity. In a nearshore environment, which is defined by shallow water areas, one type of WEC system solution is to install an oscillating wave surge converter that acts as a pendulum under the wave action. Lastly, in offshore regions, the most promising results come from the attenuator, point absorber and terminator devices.

Over 50% of the WECs are found in from Europe with most R&D focused on the point absorber system. Other countries undertaking important wave power research are the USA, New Zealand and Chile [28]. Table 1 and Table 2 present in detail the main WEC technologies. Systems may be fixed, submerged or floating. The systems can be used as independent generators or as part of breakwaters or harbor infrastructure. Most of the systems are still in the R&D stage, and the rated capacity may vary from 15 kW to 5900 kW; some point absorbers appear underrated and they could be developed into wave farms in the future.

A point absorber system used widely is the CETO 6, a buoyant generator defined by a diameter of 20 m, which was gradually increased in capacity from 80 kW (in 2011) to 240 kW (in 2015). This project is implemented in various coastal environments, including the Mauritian island of Rodrigues (project of €667 000), Garden Island, Western

Australia (€9.1m) and the CETO 6 Wave Hub Project in Cornwall, southwestern England (€16m) [33]. In terms of generating capacity, the Wave Dragon is one of the largest WECs being designed for the offshore environment. The first prototype was developed at Nissum Bredning (Denmark) in 2003 with a 237-tonne version costing approximately €4.35m. Another Wave Dragon project was developed off Milford Haven (in 2007) on the southwestern coast of Wales, and deployed in an area of 0.25 km<sup>2</sup> [34].

WECs are similar to wind turbines, wherein the performance of a particular generator takes into account a power curve. In the case of WEC devices, the manufacturer uses a power matrix that shows various power outputs according to a particular sea state (wave heights and wave periods). The power output results are calculated from the following equation [32]:

$$P_{WEC} = \frac{1}{100} \cdot \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} P_{ij} \cdot p_{ij} \quad (1)$$

where  $P_{ij}$  is the energy percentage corresponding to the bin defined by the column  $j$  and the line  $i$  and  $p_{ij}$  is the electric power provided in the power matrix of the WEC for the same bin. As an example, Fig. 4 presents the power matrix of a WEC system, rated at a maximum 250 kW, and the bivariate distribution of the wave parameters  $H_s$  (significant wave height, in meters) and  $T_e$  (wave period, in seconds).

Various indicators are used to identify the wave energy potential and the efficiency of a WEC. A common way to show the energy level of a site is through the wave power density ( $P_w$ ), expressed as [32]:

$$P_w = \frac{\rho g^2}{64\pi} T_e H_s^2, \quad (2)$$

where  $P_w$  is the energy flux per meter of the wave crest (kW/m),  $\rho = 1025 \text{ kg/m}^3$  is the density of the seawater and  $g$  is gravity acceleration. Note that Equation 2 is used to

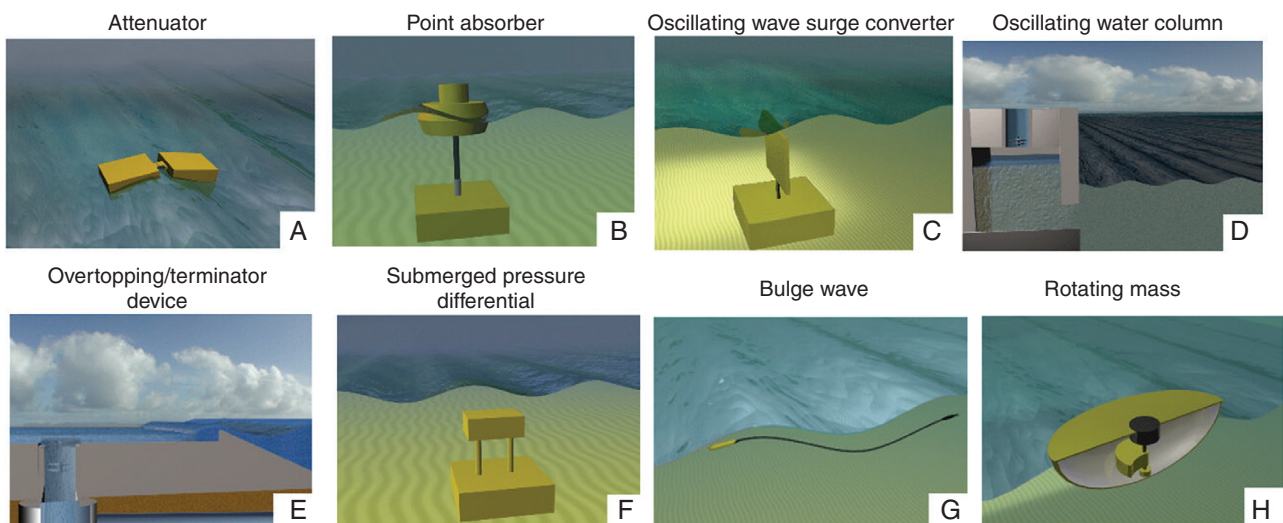


Fig. 3 Main categories of WECs [Reproduced from Ref. 31 with permission from the European Marine Energy Centre LTD]

**Table 1** Wave energy converter technologies [13]

Technology	System	Principle	Project
Oscillating water column	Fixed	Isolated; in breakwaters; nearshore	Pico; LIMPET; Sakata
	Floating	—	Mighty Whale; Oceanlinx
Oscillating bodies	Fixed-shoreline	—	Eco Wave Power
	Floating	Translation (heave)	AquaBuoy; Wavebob
		Rotation	Pelamis; SEAREV
	Submerged	Translation (heave)	AWS
		Rotation	Oyster; WaveRoller
Overtopping	Fixed	Shoreline	TAPCHAN; SSG
	Floating	—	Wave Dragon

**Table 2** Main features of commercial WEC systems [28, 32]

Category	Device	Dimensions	Capacity (kW)	Projects to Date
Point absorber	Pontoon Power Converter (PPC)	80 m	3619	R&D phase
	Ocean Energy buoy (OE)	50 m	2880	R&D phase (1:4 scale model)
	Wavebob	20 m	1000	R&D phase (1:4 scale model)
	CETO	7 m	260	Garden Island, Western Australia
	Seabased AB	3 m	15	Wave Hub, Cornwall, UK Pre-consented (3 MW each project)
				Sotenäs, Sweden Pre-consented, 10-MW demonstration plant
Attenuator	Sea Power	16.75 m	3587	Galway Bay, Ireland, test site
	Wave Star	70 m	2709	Hanstholm, Denmark (1:2 scale model, 600-kW machine)
	Pelamis	150 m	750	Aguçadoura, Portugal (2.25-MW project) Company – Financial problems
Terminator	Oceantec	52 m	500	Sea trials – 1:4 scale model
	Wave Dragon	–	5900	Nissum Bredning, Denmark, prototype testing

describe the wave power only from the deep-water areas, this being also the case of the present work where some offshore references sites were considered for assessment. For a particular water depth, the wave energy flux can be calculated by using the formula presented in Venugopal and Reddy [36]:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} S(f, \theta) \cdot \bar{C}_g(f, \theta) df d\theta \quad (3)$$

where  $S(f, \theta)$  is the directional energy spectral density at frequency  $f$  and wave propagation angle  $\theta$ , and  $\bar{C}_g(f, \theta)$  is the resultant wave group velocity.

The capacity factor ( $C_f$ ) is frequently used to define the WEC performances. This indicator can be defined as

$$C_f = 100 \cdot \frac{P_E}{R_p} \quad (4)$$

where  $P_E$  is the the electric power extracted by a WEC and  $R_p$  represents the rated power of each system. The portion

of the wavefront from which a WEC will extract energy is associated with the capture width (in meters), as follows:

$$C_w = \frac{P_E}{P_w} \quad (5)$$

Table 3 lists some common values reported by scientists from some state-of-the-art WECs for various coastal environments.

### 3 Hybrid wind-wave projects

Wind and wave action are closely linked. Therefore, the next step in the development of the marine renewable sector will be development of co-located hybrid or island systems [37]. Hybrid projects combine floating wind turbines (e.g. WindFloat system) with wave energy converters in order to capture the energy from the offshore area and reduce the initial investments. In this category, new or existing harbor infrastructure could develop hybrid systems combining electricity production with harbor protection [38, 39].

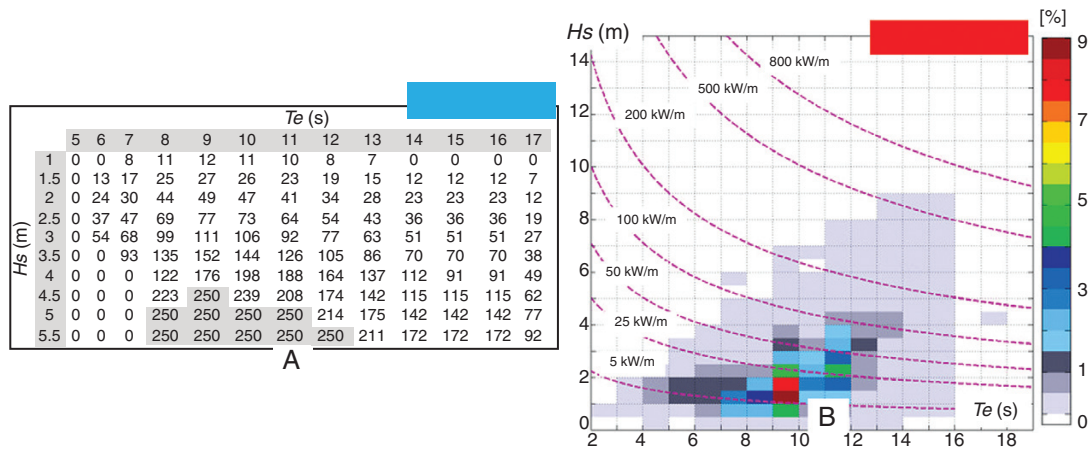


Fig. 4 The power matrix of the Aqua Buoy system (a) and the bivariate distribution of the sea states (b) reported for the Leixoes area (Portugal) [35]

Table 3 Average values of the capacity factor (%) and the capture width (m) reported during the winter [28]

		Region			
		Iceland	Azores Islands	Madeira Archipelago	Canary Islands
WEC	Cf	43.4	42	28.8	21.7
	CW	62.1	49.4	50.2	66.4
Pontoon Power Converter		9.45	5.58	4.23	3.48
		10.1	4.32	4.76	7.06
Sea Power		17.1	15.4	10.1	7.08
		13.7	10.2	10.2	12.1
OE		11.7	10.4	6.25	4.06
		8.51	5.48	5	5.5
Wave Star		13.8	12.5	7.57	4.84
		9.41	6.27	5.69	6.27
AWS		23.6	23.2	16.9	11
		9.68	10.3	11.1	11.5

The attractiveness of such projects is given by the mixed energy output defined by a higher density power and a smooth integration into the grid network, which will be less influenced by the variability of a single resource. For example, if the wind is not blowing the waves could be used to generate electricity. If the generators share the same infrastructure, it will be possible to cut the initial installation cost, especially in the case of the wave systems. Consequently it could be possible to accelerate the WEC's transition from the R&D stage to a full operational wave farm. The use of this integration approach allows one site to generate energy from two types of technology wind and wave. The WECs integrated into the existing offshore wind project, will generate a shadow effect by reducing the wave height and extending in this way the time interval allocated for operation and maintenance activities [40–42]. In this case, the number of suitable sites will significantly increase using areas with moderate resources, such as enclosed sea basins [43, 44].

Fig. 5 presents two types of hybrid wind-wave systems that are capable of exceeding R&D levels. The Wave Trader is designed for offshore wind turbines and also available in a moored version. The Floating Power Plant is another

interesting design that involves several pontoons and wind turbines working on a ship platform. In general, the hybrid systems developed currently are based on modified versions of these two concepts.

There are currently no operational large-scale wave farms, so most of the research on this topic is focused on various hypothetical scenarios. One option being focused on is the development of a large-scale wave farm in unison with wind turbines.

An advantage of using WECs to extract energy from waves is that an operational wave farm will protect the beach sectors against erosion induced by the wave and longshore currents. On a local scale it is expected that the changes in the water velocities and sediment rate will be significant. The erosion patterns may change along a particular coastline (positively or negatively) and will depend on local wave conditions and coastline features [19]. Experiments carried out in the Lews Castle College lab facilities highlighted that a farm of WECs can be efficiently used as a coastal protection system [47].

Fig. 6 highlights two case studies in which an assessment was made of the impact of different wind-wave



Fig. 5 Hybrid wind-wave platforms: (a) Wave treader [45], (b) Floating power plant [46]

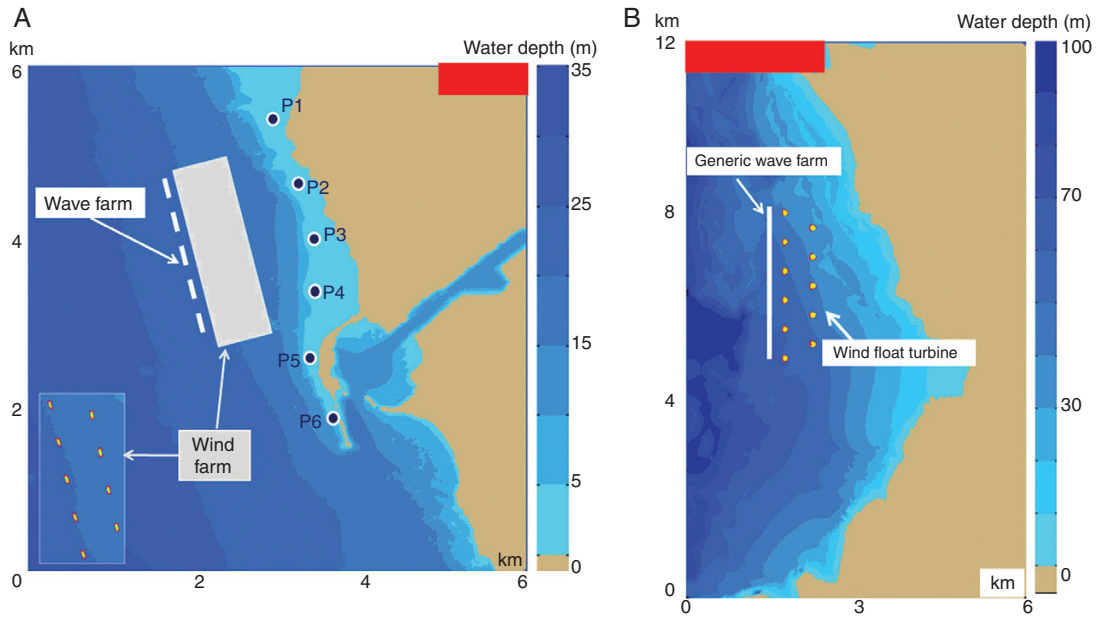


Fig. 6 Co-located wind and wave farm scenarios reported for various coastal environments: (a) Leixoes (Portugal) [35] and (b) Porto Ferro (Sardinia) [48]

projects on the local wave field. The results indicated that the shadow effect may depend on factors such as the wave direction, the spatial orientation of the marine farm, shoreline, wave intensity and the absorption property of the farm. In order to protect a particular beach sector, it is important to identify first the local wave pattern and then to identify an optimal WEC configuration, taking into account the domino effects that may occur in the neighboring coastal sectors. Table 4 illustrates analysis for the Leixoes area (Portugal, near the city of Porto), with consideration of various wave conditions and absorption scenarios.

### 4 Wave energy cost prediction

In comparison to other sources of renewable energy, wave energy is still too expensive. However, the potential of wave energy is the best option to accelerate the use of wave technology. Research on reducing the costs is a key element in encouraging the development of wave energy. In

general, it is estimated that the main costs of a wave project are related to initial investments (34.68%), operation and maintenance (O&M; 40.19%), replacement (24.81%) and preoperating costs/decommissioning (0.33%), respectively [37]. Examples of wave energy converters prices are Wave Dragon (rated power 7000 kW), €14238 652/unit; Pelamis (750 kW), €21188 470/unit; and AquaBuoy (250 kW), €169 507/unit [37].

The levelized cost of electricity (LCOE) index shows the competitiveness of a generating technology by taking into account all costs that may occur during the lifetime of a particular project. If we consider that the O&M costs and the power generated are constant, the LCOE has the expression [49]:

$$LCOE = \frac{SCI + SLD}{87.6 \cdot LF} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{OM}{87.6 \cdot LF} \quad (6)$$

where *SCI* is the capital cost of the power plant (€/kW), *SLD* is the specific levelized decommissioning cost (€/kW), *LF* is the load factor of the facility, *r* is the discount rate, *n* is the

**Table 4** Attenuation of wave heights (in %) in the presence of the wind-wave farm as reported in the Leixoes target area [35] (MA, moderate absorption; HA, high absorption)

Case study		Reference point					
		P1	P2	P3	P4	P5	P6
CS1 – average total time	MA	3.7	13.77	15.88	14.02	4.49	2.92
	HA	6.79	23.91	27.65	24.39	6.74	4.09
CS2 – average winter		2.94	14.69	12.74	10.53	2.67	2.29
		5.04	26.07	24.32	19.43	4.2	3.43
CS2 – storm event		1.33	11.26	7.16	4.71	1.72	1.74
		2.93	22.25	14.58	9.42	2.95	2.33

facility lifetime (year) and OM is the annualized O&M cost (€/kW). This expression includes:

$$LF = \frac{AEP}{87.6 R}$$

$$SLD = \frac{SDC}{(1+r)^n} \quad (7)$$

where AEP, the annual energy production (in kWh), is reported for a system at rated power R (in MW) and SDC is the specific decommissioning cost at the end of a lifetime (€/kW).

Without large operational wave farms there is no viable source of data that could be used for a cost analysis, and therefore most existing studies are based on various “what if” scenarios [50–52]. Similar to other renewable sources, the methodology used to assess economic performance comes from other areas, such as the oil and gas industry [53].

Onshore wind industry analysts estimated that the LCOE may have values in the range of 40–115 €/MWh, which correspond to capacity factors of 15–46%. Europe has an average value of 80 €/MWh compared to the USA, where an average value of 83 €/MWh is reported. The offshore industry operating in the Western Europe has an average LCOE of 218 €/MWh corresponding to a capacity factor of 32–42%. In the case of solar PV, we expect LCOE values in the range 67–372 €/MWh obtained for capacity factors of 11–21%. In terms of geothermal systems, a maximum LCOE of 234 €/MWh may cover a capacity factor of 95% [54]. For hydroelectricity, a small system can be expected to obtain values in the range of 16–266 €/MWh compared to a larger system where the values are 20–256 €/MWh. The tidal and wave energy sectors reveal similar trends, being divided between high-, medium- and low-cost scenarios. The following numbers give an estimated cost, from high to low, of generating wave energy: high cost, €14/MW (CAPEX), €127 130/MW/yr (OPEX), 25% (capacity factor), €897/MWh (LCOE); medium cost, €7.44/MW, €127 130/MW/yr, 30%, €420/MWh; low cost, €4.64/MW, €127 130/MW/yr, 35%, €241/MWh [54].

## 5 Conclusion

To succeed, wave energy R&D projects need to identify ways to reduce the cost of electricity and to find a suitable

protection mechanism for the WECs in order to survive the weather and the harsh, corrosive marine environment. Most studies investigate these problems only on a theoretical level. The current pre-commercial systems (e.g. Wave Dragon, PowerBuoy, Pelamis, Wave Roller, Archimedes Waveswing [AWS]) are the result of collaboration between industry and the academic sector [55]. However, this is not a guarantee of the success of a particular design with most WECs reporting both negative and positive aspects.

The attractiveness of a particular site depends on factors such as the wave height and direction and it is also restricted by whether the site is in a protected area or near shipping routes. Since the WEC generator is still in its infancy, a practical solution is to utilize other marine projects (e.g. wind farms) to accelerate industry development. In the case of a wind-wave project, this may compensate for the wind variability, which is considerably higher than in the case of the waves and more difficult to predict.

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Conflict of interest statement. None declared.

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