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The economics of wave energy: A review

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ABSTRACT

Wave energy is arguably one of the most promising renewables. Less developed at present than other renewables, the existing models to estimate the costs of a wave energy project are often oversimplified, and the resulting scatter in the economic assessments weighs on the confidence of potential investors and constitutes therefore an impediment to the development of wave energy. Indeed, understanding the costs of wave energy is one of the main fields of research in marine renewable energy. In this context, the main objective of this paper is to review all the factors that must be considered in an economic analysis of wave energy, including a number of elements that are usually overlooked. In the process we characterise the direct and indirect costs of a wave farm – preliminary costs, construction, operation and maintenance and decommissioning cost – as well as its prospective incomes. For each of them a reference value is presented, together with a generic formula for its calculation. Moreover, the levelised cost, i.e., the production cost of an energy unit (1 kW h), is compared between various energy sources, and on these grounds conclusions on the profitability and competitiveness of wave energy are drawn. In sum, this work reviews the state of the art and sets the basis for a thorough economic analysis of wave energy.

Contents

1. Introduction

In 2007 the European Union (EU) undertook to transform Europe into a highly energy-efficient and low-GHG economy, committing to reduce 20% of CO_2 emissions, to reduce 20% of energy consumption and to achieve the target of a 20% of the total energy consumption of the EU made up of renewable energy (Directive 2099/28/EC). The main focus of this policy has been on wind and solar energy. In order to reach the desired percentages, however, it is necessary to develop other forms of renewable energy less developed at present but with high potential [1,2], such as marine energy—carried by ocean waves, tides, salinity, and ocean temperature differences. Among these different alternatives, this paper is focused in wave energy [3,4] which, although it is in an initial stage of development, presents extensive possibilities for the future thanks to its enormous potential for electricity

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Nomenclature

$C_{elect.inst.}$	cost of the electrical installation (€)
$C_{initial}$	initial cost (€)
$C_{mooring}$	cost of the mooring system and its installation (€)
$C_{subest.}$	cost of the electrical substation (€)
C_t	the stream of (real) future costs
$C_{und.cab.}$	underwater cable cost per unit of length (€/m)
$C_{subt.cab.}$	underground cable cost per unit of length (€/m)
C_{WEC}	cost of one converter and its installation (€/WEC)
CALM	catenary anchor leg mooring
CAPEX	CAPital EXpenditure (€)
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CER	European waste catalogue
d	diameter of the chain (mm)
ETS	European trading scheme
EUA	dealing of carbon credits among companies
f_e	efficiency of electrical energy conversion
f_m	mechanical efficiency of conversion and the hydrodynamic power of a farm
f_t	efficiency of electrical energy transmission
FIT	feed-in-tariff (€/MW h)
GDP	gross domestic product
GHG	greenhouse gas
h	water depth (m)
HVDC	high voltage direct current
IGCC	integrated gasification combined cycle
K	a constant with value 0.02 kg/(m mm^2) for studless chain and 0.0219 kg/(m mm^2) for stud-link chain
L	length of the chain (m)
LC_D	levelised costs measure under the discounting method (€/MW h)
$L_{offshore}$	meters of underwater electric cable (m)
$L_{onshore}$	meters of underground cable until the electrical network (m)
N	number of converters
O_t	stream of (real) future (electrical) outputs
O&M	operation and maintenance
OPEX	operational expenditure
OWC	oscillating water column
P_{Chain}	weight of the chain (N)
P_f	final power of the whole installation (W)
P_h	hydrodynamic power (W)
P-Val	present value. This factor can be referred to costs or power output (€, MW h)
PV	photo voltaic
PWR	pressurized water reactor
r	discount rate (interest rate used to bring future values into the present)
t	a point of time (s)
T	service life of the wave farm (s)
WEC	wave energy converter

production [5–19], in the same way than tidal or offshore wind energy [20–29]. In fact, the global wave energy resource is estimated at 17 TW h/year [30], with the largest values of average wave power in the mid-latitudes (between 30° and 60°) (Fig. 1).

Nevertheless, the main barriers in the development of marine energies are: (i) the early stage of development of the technologies [32–40], (ii) the uncertainties regarding the coastal and marine impacts of wave farms [41–51], and (iii) the fact that they have been considered uneconomical [52]. In this sense, the importance of the economic evaluation of wave energy can hardly be overstated—indeed, economic viability is a sine qua non condition for the development of this novel renewable; it involves a detailed evaluation of costs and private profits (income) associated with investment on these technologies. This way, the vast majority of studies about this field [22,53–58] are based in this last point; indeed, it is possible to find studies on wave energy profitability at specific locations according with the current charging system. For example, [56] or [57] are focused on the Irish economy, [53] on the UK and [54] analyses the effects on the Scottish economy of installing 3 GW of wave energy: effect on GDP (Gross Domestic Product), creation of new jobs, and so on. However, since wave energy technology is in an initial stage of research [59] and it is difficult to estimate the costs and performance of the device and the rest of the installation, the most part of current economic studies are oversimplified, and this could create insecurity in investors. In this context, this paper establishes the different costs incurred in a wave energy farm, their expected values and future evolution. With this information, the levelised cost (€/MW h) is

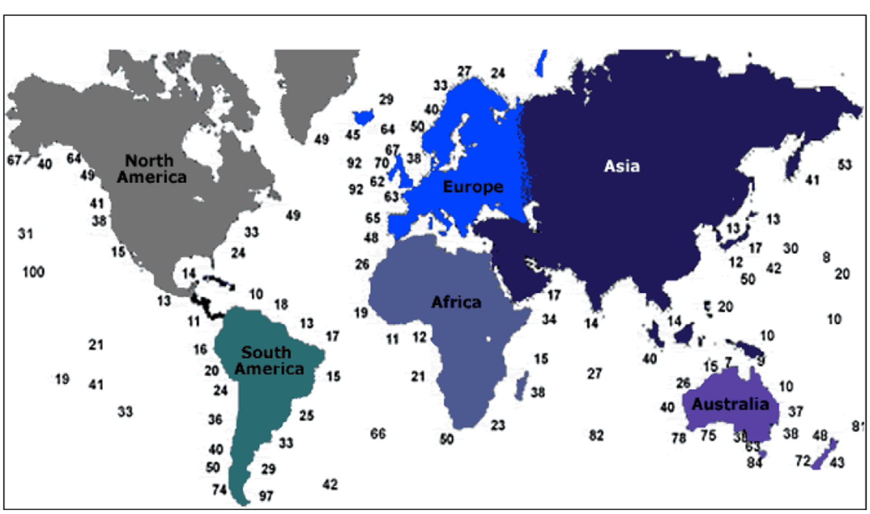

Fig. 1. Global distribution of the wave energy resource (average wave power in kW m^{-1}) [31].

Table 1
Pre-operating and licenses costs.

Category	Cost	Source
Pre-operating cost	10% CAPEX (€)	[55,63]
	500,000–2000,000 €	[64]
Licenses and permissions	0.037 × Installed power in W ($)	[22]
	2% WECs cost (€)	[55,63]

Table 2
WEC cost per MW [68].

WEC power (MW)	€/MW
0.25	5000,000
0.5	4000,000
1	3000,000

calculated and compared with that of other energy resources; also in addition, the expected incomes of wave energy farms are analyzed. The present study is concerned with offshore wave energy farms, since this type of farm is closest than any other to commercial development [60,61], and based on it, a complete and detailed analysis of the profitability of a wave energy plant can be developed.

2. Wave farm costs

The main costs in a wave energy plant are the following: (i) pre-operating cost, (ii) construction costs, (iii) operational expenditure (OPEX), and (iv) decommissioning costs.

The pre-operating cost includes the costs of preliminary studies, projects, environmental impact assessment, consenting procedures, etc., as well as direction and coordination. Establishing a generic value for this cost is a complex process, since it depends very much on the type of installation, location and particular characteristics of the project at hand [62]. It is often considered as 10% of the capital expenditure (CAPEX) [55,63]. The Association of Renewable Energy Producers estimates that it ranges between 500,000 € and 2000,000 € [64]. Then, the costs associated with procedures for licenses and permissions need to be added; these are estimated as 2% of the initial cost of WECs [55,63] or, more specifically, as 3.7% of the power of the plant (W) in US dollars [22], i.e., for a 100 MW plant, the cost of permissions and licenses would amount to $3.7 M (or 28,000 €/MW). The aforementioned information is summarised in Table 1.

As for the initial cost ($C_{initial}$), it refers to the amount necessary for purchasing the Wave Energy Converters (WECs) and other elements of the wave energy plant, as well as for its installation:

$$C_{initial} = N \times C_{WEC} + L_{offshore} \times C_{und.cab.} + L_{onshore} \cdot C_{subt.cab.} + C_{subest.} + C_{elect.inst.} + C_{mooring} \quad (1)$$

where N is the number of converters, C_{WEC} is the cost of one converter and its installation, $L_{offshore}$ is the length of underwater electric cable, $C_{und.cab}$ is the cost per unit length of underwater cable, $L_{onshore}$ is the length of underground cable up to the existing electrical network, $C_{subt.cab}$ is the cost per unit length of underground cable, $C_{subest.}$ is the cost of the substation, $C_{elect.inst.}$ is the cost of the electrical installation, and $C_{mooring}$ is the cost of the mooring system and its installation.

The WEC price comprises the purchase of the device, together with the cost associated with its installation. After analyzing and comparing different studies and sources [65–67], it can be inferred that the cost of equipment and installation lies between 2.5 and 6.0 M€ per installed MW. Table 2 shows reference values for the cost of the converter per MW of installed power; information on the costs of three WECs close to the market is presented in Table 3.

Table 3
Rated power and estimated cost of WaveDragon, Pelamis and AquabuOY [69–72].

Technology	WaveDragon	AquabuOY	Pelamis
Rated power (kW)	7000	250	750
Estimated cost ($/MW)	2400	800	3333
Estimated cost ($/unit)	16,800	200	25,008

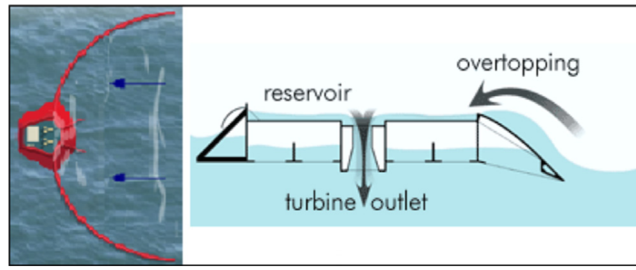

Fig. 2. WaveDragon device [73].

WaveDragon (Fig. 2) is an overtopping device that elevates ocean waves to a reservoir above sea level, from where water is let out through a number of low-head hydro turbines and in this way transformed into electricity [74]. Pelamis (Fig. 3) is an attenuating wave energy converter that uses the motion of waves to generate electricity. It is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams which pump high pressure fluid through hydraulic motors via smoothing accumulators, which drive electrical generators to produce electricity. [77]. Finally, AquabuOY (Fig. 4) is a floating device consisting of a buoyant float connected with a piston that is inserted into a cylindrical tube that is flexibly moored with the sea floor. When the float bobs up and down, the water is pressurised by the piston cylinder assembly and the pumped water is used to drive a turbine which produces electrical energy [79].

Other important element in an offshore wave farm is the mooring system, which has been addressed in the last years by several authors [80–86]. In general, its costs can be estimated as 10% of the WEC cost [53,55,63]. There are different options as a function of the line, its material and the type of mooring employed. Table 4 presents a comparison matrix of three common mooring systems: (i) the *system with catenaries* allows the movement of the structure in any one of the six degrees of freedom, with lines made of chain until depths of 250–300 m [87]; (ii) *the taut system*, which not only bears horizontal but also oblique loads; in this case, it is the rigidity, and not the weight, that acts as restoring force: in consequence, the radius that the system covers is smaller [89,90]; and (iii) *the TLP system*, the most complex and costly, consists in vertical lines that attain the required tension thanks to the excess of buoyancy provided by the structure. The lines can be wires, tubes, steel bars, etc. [91].

The analysis in Table 4 shows that the most appropriate mooring is the catenary system, which is commonly known as CALM (catenary anchor leg mooring). This is well in line with previous analysis [93–95]. Albeit not without downsides (greater length and weight), other factors, e.g., easy installation, lower cost, or the fact that it is less affected by the corrosion, make it the best option in most cases.

For this system, the cost of mooring lines is calculated based on their diameter and length. Then, its weight is obtained (Eq. (2)) and, finally, the cost per unit weight (0.265€/N) is applied (Eq. (3)) [96]. Moreover, it is necessary to add the installation cost, which is

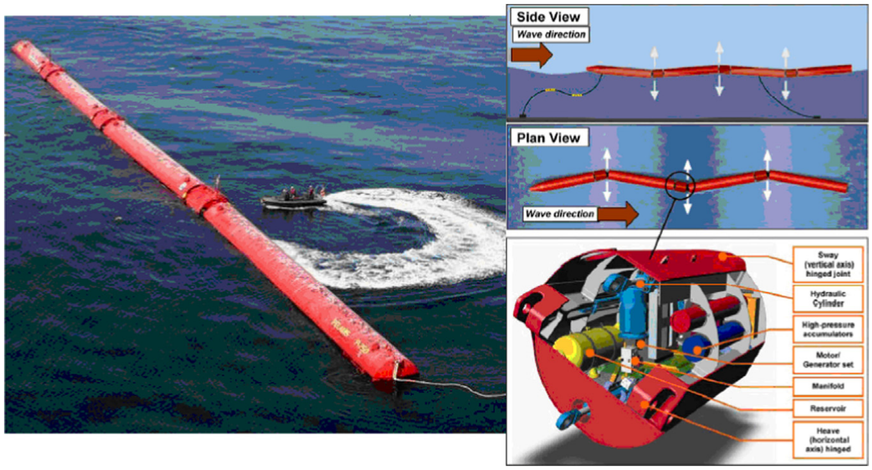

Fig. 3. Pelamis wave energy converter [75,76].

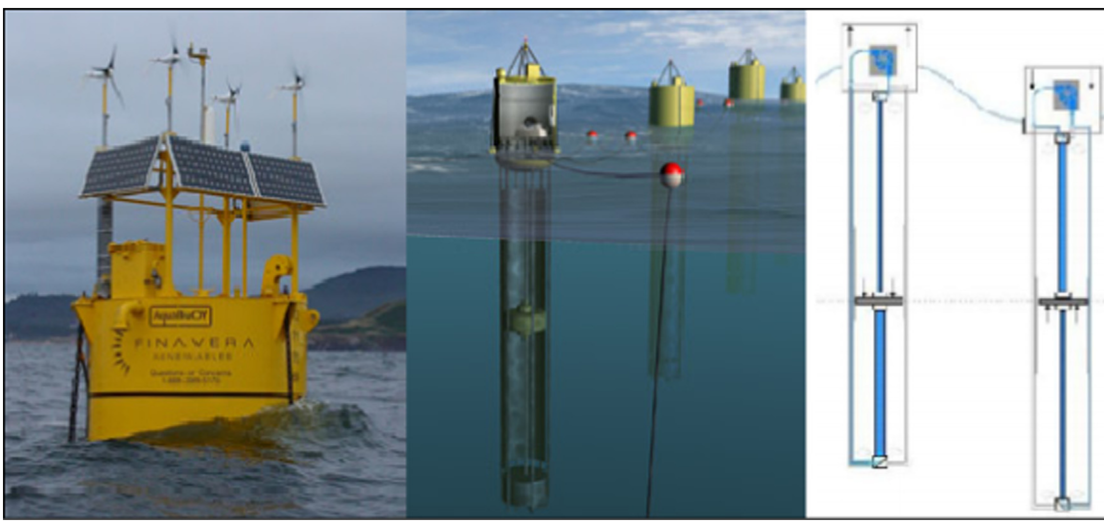

Fig. 4. AquabuOY wave energy device [78].

Table 4
Mooring system comparison. [84–92].

	Catenary	Taut	TLP	Factor weight	Catenary	Taut	TLP
Length (of the line)	1	2	3	3	4	8	12
Weight (of the line)	1	3	2	2	2	6	4
Compatibility with kind of anchorage	3	2	1	1	3	2	1
Effect of the growth of marine fauna	3	1	2	2	6	2	4
Complexity of the installation process	3	2	1	4	12	8	
Affected zone by the moorings	1	2	3	3	3	6	18
Corrosion effect	3	2	1	3	9	6	3
Design requirements for the platform	1	2	3	2	2		6
Comprehensive anchor	3	3	0	5	15	15	0
Not variation in the position	1	2	3	4	4	8	12
Line cost	3	2	1	4	12	8	4
Installation cost	2	2	1	4	8	8	4
Tidal effects	3	2	1	1	12	8	4
Environmental impact	1	2	3	4	4	8	12
Know how local	3	2	1	2	12	8	4
Total	2.13	2.07	1.73		7.2	7.0	6.13

conditioned by the cost of the vessel, of the order of 50,000 €/day [93].

$$P_{Chain} = 9.81 L d^2 K \quad (2)$$

$$Cost_{chain} = 0.265 P_{chain} \quad (3)$$

where P_{Chain} is the total weight of the chain (in N), L its length (m), d its diameter (mm), and K is a constant with a value 0.02 kg/(m mm^2) for studless chain and 0.0219 kg/(m mm^2) for stud-link chain. The total length of the mooring line (L) is usually estimated as 3–5 times the water depth (h): [97] used 5h, [98] used 4h, and [99] suggested 3h.

Apart from WECs and moorings, the wiring and electrical installation are the basic elements in a wave farm. To determine their cost, first of all, it is necessary to choose the type of power output, i.e., direct current or alternating current. The latter can be easily transformed but, in the case of underground and underwater lines, entails relevant losses due to the conductors' capacitance [100]. At present high voltage direct current (HVDC) is under study as a most effective alternative for evacuation and transport of energy; however, this system is still very costly [101–104]. For this reason, and given that the distances between coastline and the wave plant are usually below 5 km and high tensions are not commonly used, the best option for the time being is transporting in alternating current,. The required length of underwater cable depends basically on the distance to the shore, but in the case of more than one WEC (a wave farm) it will also depend on its layout. The WECs in a wave farm are generally grouped and then connected in series, with each group attached to a hub [105]. The spacing between devices will define the cable between converters, and it depends on the kind and number of devices, and also the wave climate. It is clear that the smaller the length between devices, the lower the cost of the cable and mooring system. However, the spacing selected will also influence the interactions between devices and the wave field, and the performance of the installation can be lower if the WECs are too close. On the contrary, if the array spacing is large compared with the size of the WECs the direct interactions can be neglected [106,107], but the capital cost will be greater as the mooring and submarine cables will be more expensive. Some studies consider a spacing of 100 m [108,109], whereas others assume smaller spacing values [110]. In some cases [111, 112] the spacing is given as a function of the device diameter, with a typical value of 10 times the diameter; finally, in other cases the spacing is given as a function of the wavelength, namely 75–100% of the wavelength [105,106].

Another issue to take into account is that the underwater cable has to be used also on dry land for a sufficient security distance, which is around 250 m [113]. Once all the specifications of the electric cables are defined, and the sections determined, the cost can be looked up in the manufacturers' catalogs. As a first estimate, the value can be calculated as 10% of the initial costs [56,58]. In addition, the installation cost has to be considered, especially for the underwater cable. This value is around 0.20 €/m, and the cost of the required vessel is approximately 1.87 €/m [106]. Apart from the costs of the cable, it is necessary to take into account the other elements of the electrical installation. The most relevant is the electrical substation, whose cost varies with the tension elevation required to deliver electricity to the network. For example, the cost of a substation to elevate the tension from 11 to 33 kV is of 1110,000 €, and from 11 to 66 kV, 1330,000 € [107]. Table 5 summarizes the above information about the initial cost of a wave farm and the subcategories involved.

As well as the initial investment, the operation and maintenance cost (OPEX) must be included in an economic analysis. Calculating this cost is a complex process, since there is not enough experience in wave energy installation. Nevertheless, it is possible to obtain a first estimate based on the experience in the oil and gas and offshore wind energy sectors. In Table 6, some of these costs are collected in €/MW h and/or as a percentage of the CAPEX or the OPEX. A detailed methodology to work out the cost of both routine and emergency maintenance is presented in [22].

Besides, it is necessary to consider that ten years after their first installation, the WECs have to be removed from the sea for an overhaul, including repainting and replacement of some elements, such as hydraulic cylinders. The estimated cost is approx. 4.2% of the initial costs [93]. Moreover, the whole plant is supposed to be dismantled after 20 years and the decommissioning cost is estimated to be 0.5–1% of the initial investment [64,124,125]. Another study [126] considers that the average decommissioning costs would be around 50,000€/MW. Apart from that, there are other important factors related to O&M costs, such as the availability and failure rate. The availability is a key player in the profitability of a wave farm since it is the amount of time the device is on hand to produce power; it is affected by a number of factors, including device reliability and the ability of the device to be accessed for maintenance [58,127]. The levels of access to wave energy devices are likely to be lower than offshore wind, due to the more aggressive wave climates that the wave devices will be deployed in, as well as the fact of the devices themselves not being stationary, making access from floating vessels even more difficult. As a result, availability levels for wave energy may be lower than 90% [58,128–130]. As regards the failure rates, the WEC system can be divided in four different sub-systems: (i) mooring; (ii) structure; (iii) power take-off system; and (iv) power transmission system. A failure rate of 0.185 was obtained [131] for the mooring system. As regards the structure, assuming the comparability of single-hull oil tankers and the structural housing of the WEC, an indication of expected failure rates can be established as 0.011 [132]. The failure rate of the joints is extremely difficult to estimate, as information is virtually not available in the public domain neither on design nor on expected loads. However a failure rate of 0.315 has been proposed [133]. Finally, Table 7 reflects the failure rate associated to the power take-off system and power transmission subsystems.

Table 5
Summary of initial costs.

Element	Cost	Source
WEC and installation	2.5–6.0 M€/MW	[65–67]
Mooring system	10% WECs cost	[53,55,63]
	0.265 €/N	[96]
Mooring installation	50,000 €/day	[93]
Underwater cable	10% CAPEX	[56,58]
Cable installation	2.07 €/m	[106]
Electrical substation	≈ 1.2 M€	[107]

Table 6
Annual costs of operation and maintenance [58,63,68,114–123].

Cost	€/MW h	% CAPEX	% OPEX
O&M tasks	20–35	1.5–5%	57%
Revision and time off		10	
Spares		90	
Public services	3.5		
Renting		2.5	
Insurance cost	15	0.8–2%	13–14%

Table 7
Failure rate of the power take-off system and power transmission subsystems [131–137].

Power take-off		Power transmission	
Component	Failure rate	Component	Failure rate
Hydraulic ram	0.24	415 V busbar	0.01
Manifold	0.004	Transformer	0.07
Accumulator	0.42	Circuit breaker	0.26
Hydraulic motor	0.17	Umbilical	0.04
Electric generator	1.59	Sea cable	0.09

Table 8
Levelised cost estimates for ten electricity generation technologies [53,145,146].

Technology	Cost (€/MW h)
Onshore wind	67.68
Offshore wind	101.43
PWR nuclear (pressurized water reactor)	49.96
CCGT (combined cycle gas turbine)	43.17
IGCC coal (integrated gasification combined cycle)	36.59
IGCC coal with CCS (carbon capture and storage)	55.76
Retrofit coal	44.40
Pulverized fuel	32.57
Pulverized fuel with CCS	50.79
CCGT with CCS	59.78

3. Levelised cost of wave energy

The cost of energy production remains perhaps the single most important factor in determining whether an energy technology can reach commercialization. To properly assess the cost of a specific energy conversion technology it is necessary to develop a standard by which we can compare the various technologies. One such standard is the levelised cost, which is widely reported in the energy policy literature [53,138–142]. It is the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent [141]. There are different models to calculate the levelised cost. In this work the discounting method [53,66,141] is used. The levelised costs measured with the discounting method, LC_D, is given by Eq. (4): the stream of (real) future costs and (electrical) outputs, identified as C_t and O_t in period t, are discounted back to a present value (*P-Val*). The *P-Val* of costs is then divided by the *P-Val* of lifetime output:

$$LC_D = \frac{P-Val\,(\text{Costs})}{P-Val\,(\text{Output})} = \frac{\sum_{t=0}^{n} C_t/(1+r)^t}{\sum_{t=0}^{n} O_t/(1+r)^t} \tag{4}$$

In order to apply Eq. (4) it is necessary to choose a discount rate (r), which will be used to convert the stream of future costs and electrical output into their present values. The range of discount rates used for marine energy is in the range 5–15% [53,66,143,144]. To analyse the competitiveness of wave energy versus other energy sources, their levelised cost (€/MW h) is shown in Table 8.

From this data, it is easy to notice that the most economical technology is pulverized fuel, with a cost of 32.57€/MW h, whereas the most expensive non-renewable electricity generation method is CCGT with CCS at 59.78€/MW h. As for renewable energies, the cost of onshore and offshore wind energy is slightly higher: 67.68€/MW h and 101.43€/MW h respectively. In the case of wave energy, the cost ranges from 90€/MW h to 140€/MW h for onshore and nearshore plants, and from 180€/MW h to 490 €/MW h for offshore energy farms [53,147]. Naturally the actual value will vary from one country to another, and even inside a country, depending on the location, devices, distance to the coastline, and so on. All in all, it is clear that wave energy is more expensive than any non-renewable energy and also than most renewables—a result that might have been expected, for wave energy is a still in its infancy [57].

The implication is that, at present, wave energy is only economically viable if subsidized. However, over time it can be expected that promoters will realize greater investments based upon tested technology and economies of scale will thus be achieved. This would lead to reductions in costs and, consequently, investors could obtain profits and promoters could operate with market prices similar to other common renewable energies. All this is represented by means of the so-called learning curve, which identifies cost reductions arising through economies of scale and technological effects, such as technological advances and improvements by practice, for example, in the case of wave energy, the greatest chance of reduction lies in the cost of construction [53]. There are not many studies examining the impact of learning curves on the profitability of wave energy plants. Despite that, most of them agree on a learning rate of 85–90% within the next 10 years [56,53,80,11,148–151].

Moreover, for encouraging investors and ensuring a successful financial of wave energy projects, all the risks attributed to these projects need to be avoided or mitigated [152,153]. Volatility in interest rate, currency exchange rate and inflation can affect economics of project. However, wave energy technology has not matured yet and technology risks are high compared to resource risk [152,154]. The risky conditions in energy production occur during the shortage of wave heights to initiate the wave energy conversion device [155]. The risk of a failure for a wave energy converter platform with a project life of 20 is 75–90% [155,156].

4. Incomes from a wave farm

To analyze the profitability of a wave energy plant it is necessary to determine the income that will be generated. The main income stems from selling the energy produced to the electrical network, which corresponds with the integral of the final power P_f of the wave farm during its lifetime (Eq. (5)):

$$\text{Energy} = \int_0^T P_f\,dt \tag{5}$$

where P_f stands for the final power of the whole installation, t is time, and T represents the service life. Therefore, the first step is to determine the final output, and this can be calculated as follows (Eq. (6)):

$$P_f = f_t f_e f_m Ph \tag{6}$$

where P_h is the hydrodynamic power, f_m stands the mechanical efficiency of conversion and the hydrodynamic power of a farm, f_e is the efficiency of electrical energy conversion and f_t stands for the efficiency of electrical energy transmission.

To obtain the hydrodynamic power (P_h), it is necessary to multiply the power matrix of the WEC, which is a bivariate matrix indicating the average power generated by the WEC as a function of significant wave height and wave period, by the resource matrix [33,157,158]. In addition, it is necessary to take into account the losses, which are usually considered as 30% of the theoretical power [53,159]. It is also estimated that 5% of the time the farm is under repair or suffering a failure that stops electricity production [160]. This process enables to obtain the hydrodynamic power for a single WEC; nevertheless, the question in the case of a wave farm is more complex. In this case, it is necessary to take into account the interactions among converters, for example, [160] studies the power of a wave farm, and, depending on the layout, the differences in power generated can reach up to 30%.

Finally, some data on the capacity factor, which is the ratio between the average annual energy and the theoretical maximum energy, are included. It depends on the chosen WEC, its location, the kind of energetic conversion, and so on, and that is why this factor is hard to determinate. Nevertheless, some entities and authors have provided an order of magnitude for it: 20–45% [66], 22.5–35% [161], 35–40% [58]. According to the WECs' working principle: 40% for an OWC [162], 25–40% for hydraulic systems [77], 33% for pneumatic systems, 50% for OWC with hydraulic intermediate system, and 20% for direct conversion through linear generators [159]. Tables 9a and 9b show some performances of the conversion system for existing devices.

With the total energy production calculated, the income generated by its sale depends on the feed-in-tariff (FIT). This value

Table 9a
Performance of some WECs in operation [163].

Device	Efficiency		
	Primary (%)	Secondary (%)	Total (%)
OWC NEL	76	60	46
OWC QUB	20–90	50	
OWC ART OSPREY	115–60	60	
OWC Sanze	11		
OWC Kaimei	< 10		
OWC Sakata	50	36	18
OWC (BBDB)	53	60	35
OWC (Portugal)		50	
Mighty Whale	60		
OWC China			10–35
Pendulum	75		40–50
Tapchan			33
Lilypad	57	70	
OWC NEL	76	60	46

Table 9b
Comparison of performances of European WECs [163].

Device	Installed power (kW)	Absorbed annual energy (kW h)	Efficiency (%)	Annual electrical production (kW h)	Installation performance (%)
Swan DK3	203	441,234	54	23,8267	11
Point absorber	78	147,325	72	10,6074	8
Bølgehøvlen	6	4062	81	33,2920	2
Bølgemøllen	15,000	39,813,000	85	33,841,050	20
Wave Dragon	3,160	3577,740	81	2897,969	11
Bølgeturbinen	14	31,908	85	27,122	1
Wave Plunge	110	255,402	72	183,889	9
Bølgemøllen	15	9,421	72	6,783	1
DWP-system	120	236,365	72	198,875	14
Planta de Pico	400	988,455	54	539,160	18
Pelamis	597	1299,030	72	935,302	5
Mighty Whale	110	398,566	54	110	3

varies in a high degree depending on the country and it is, together with the resource, one of the most important factors for investors to decide the location. However, many changes have taken place during the last years in European policies with regard to renewable energies and, although these policies aim for a greater incorporation or marine renewables into the energetic mix, the economic support towards them is lower. The value of the selling price (€/MW h) for wave energy in the European Union is shown in Fig. 5. It is apparent that many of the countries in the European Union do not have a clear and defined policy for wave energy. And within the remaining countries there is a large disparity. The average lies around 110€/MW h.

5. Externalities

Apart from the direct profit obtained by selling the generated energy, there exists a current tendency that consists in including other indirect profits known as externalities [167–177] that have to be internalize (Fig. 6).

For example, it is interesting to take into account the profits obtained by avoiding carbon emissions when comparing wave energy with other sources of technology, since those countries that reduce their emissions more than what they agreed to have the possibility of selling the surplus carbon credits to the countries that do not fulfill their commitments. This is regulated by a Directive of the EU (Directive 2003/87/EC) defined in October 2003, which implied the beginning of the ETS (European Trading Scheme), applicable only to emissions generated by the activities regulated by the Directives 2003/87/EC and 2004/101/EC. Fig. 7 shows the evolution of the CO_2 prices in the last twelve months (September 2014).

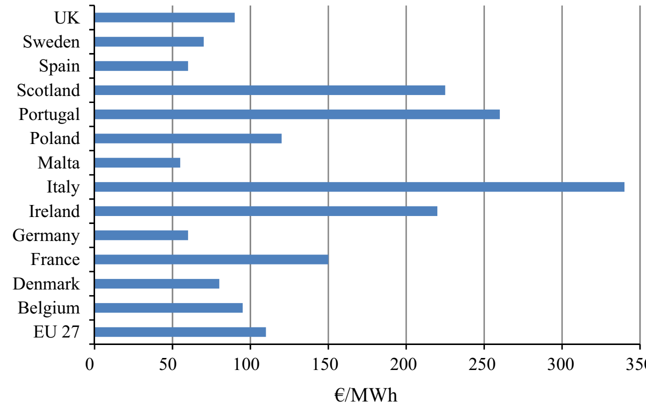

Fig. 5. Selling price for wave energy (€/MW h) in the European Union [164–166].

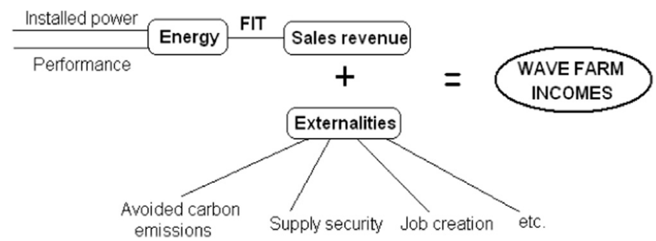

Fig. 6. New tendency to calculate the incomes providing for a wave farm including external costs apart from the sales revenue.

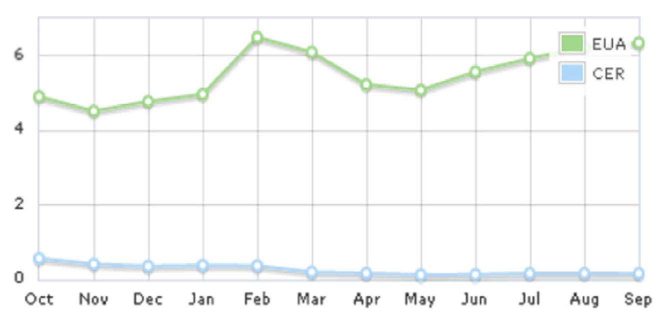

Fig. 7. Evolution of the CO_2 prices (in €/t CO_2) from October 2013 to September 2014. The dealing among companies corresponds to the line EUA in the chart, and the one among states with CER (European Waste Catalogue) [178].

There are few studies in relation to the oceanic energies and the GHG emissions produced by them. This is due to the fact that WECs are in their initial phase of development and also, because it is necessary to work with a complete and dynamic life-cycle analysis to determinate carbon emissions [179]. Even so, some of these studies estimate that carbon emissions in wave energy are 6 gCO_2/kW h of produced electricity [180], whereas the average value in Spain (2010) was 250 gCO_2/kW h [181]. So, comparing both values, a saving of 244 gCO_2/kW h might be achieved by wave energy production, which can be translated into 1.22 c€/kW h.

Another factor to be considered as an externality is the effect that the renewable energies have on the supply security, reducing the risk of supply cuts of conventional fuels, and therefore

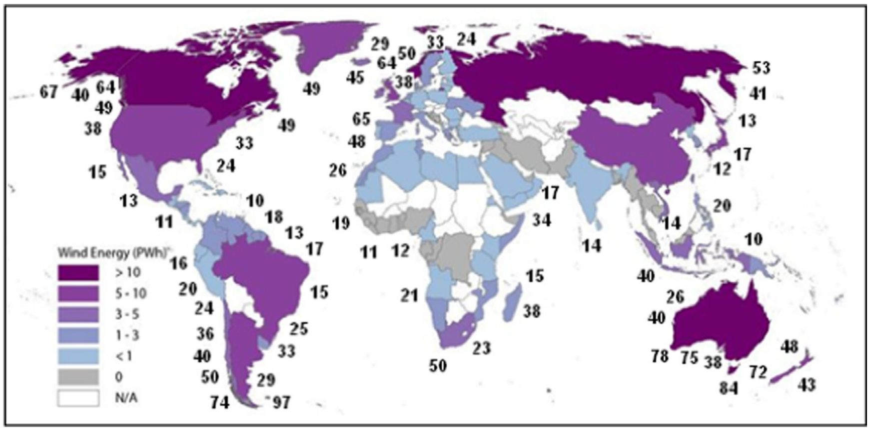

Fig. 8. Global distribution of wind and wave energy resource. The former is reflected through the colour scale in units of PW h, and the latter by means of the numerical scale in kW m^{-1} [31,197]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

avoiding important economic losses; e.g., a cut of one day in the gas supply in Spain would produce a loss of 0.03% of the GDP [182].

Other positive impacts associated with renewable energies are the creation of new jobs and integration into the economic fabric. For example, in Germany the ports of Bremerhaven and Cuxhaven had gone into a phase of economic slowing down, and they have been reactivated by the development of offshore wind energy, due to the implantation of companies specialized in wind energy or to the reconversion of companies to be adapted to this dynamic market. For example, in the year 2010, around 3000 jobs were created in those locations, although there was no offshore wind farm in that area [68].

6. Wind and wave energy combined systems: Cost savings

The idea of taking advantage of different ocean renewable resources in the same offshore installations is gaining importance [183–187] as a way to achieve a better use of the marine resource [188,189] and turn this renewable into a cost-competitive option [190]. In the case of wave energy, the combination with offshore wind energy is emerging with force due to the synergies between both renewables [191–195]. There are different possibilities for a combined wave and wind array [192,193]: (i) co-located wind-wave energy; (ii) hybrid converters; and (iii) energy islands. In all cases, wave production might increase the availability and smoothen the energy output by compensating in part for the variability of offshore wind power. Moreover, a reduced capital cost per MW installed may be achieved thanks to the common elements and equipments. In the same way, cost savings in maintenance tasks are expected due to sharing strategies and other factors such as the shielding effect of WECs over the offshore wind farm [191,192,196], which increases the weather windows for O&M. Fig. 8 reflects the global distribution of the wind and wave energy resource; it is apparent that there are some areas with large possibilities to this combined options.

7. Conclusions

In this paper a thorough review of the economics of wave energy was presented. The costs and incomes were described and quantified, and a number of uncertainties were highlighted, which can constitute a barrier for the development of this novel renewable. The cost of the WECs was found to be a very significant part of the overall cost of a wave farm. Indeed, as in the case of other renewables (e.g., solar PV, solar thermal) the capital costs of wave energy currently exceed those of conventional generation technologies (e.g., gas, coal). However, these costs can be expected to decrease with economies of scale, as wave farm deployments are undertaken; this fact, combined with rising long-term construction and uncertain long-term fuel costs for conventional generation technologies, is leading to a closure of formerly wide gaps in electricity costs. The cost of operation and maintenance is also high, as corresponds to a facility in the sea. The importance of these operations can be hardly overstated–proper and regular maintenance is necessary to maintain production capacity over the service life of a wave farm; however, their economic assessment presents a number of difficulties. One is related to replacement decisions. The need for replacement may arise because of obsolescence, early service failure, destruction, etc. It is difficult to estimate the number and type of replacement interventions that will be made, especially in respect of emergency maintenance. The experience of offshore wind installation can be used to form a preliminary idea. All in all, a MW h generated from wave power is at present more expensive than its counterpart from conventional sources and most other renewables, and hence wave power installations can only be economically viable if favoured by subsidies.

As regards the incomes from a wave farm, the sale of the generated energy is naturally the main income. In this sense, current converters have low performances, and improving them will greatly contribute to the economic viability of wave energy. As for the FIT, it varies significantly between countries and is thus one of the most important factors for choosing the location of a wave farm. In addition to the sale of the generated energy, income from selling carbon emissions credits ought to be considered in countries that adhere to the Kyoto Protocol, such as EU member-countries. These countries are subject to a cap of carbon emissions; those exceeding the limit will have to buy additional *carbon credits* from countries emitting below their limits. Further to these direct sources of income, other benefits of a wave farm could be quantified as a form of indirect income, e.g., the improvement of infrastructures in the area, the reactivation of related sectors, such as shipbuilding, which are contracting in many countries, and the creation of new jobs. Including these factors into the economic evaluation is necessary in order to derive appropriate conclusions on the competitiveness of wave energy and, more generally, renewable energies vs. conventional energies.

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