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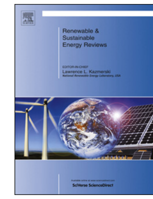

Review of wave energy technologies and the necessary power-equipment

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ABSTRACT

The wave energy is having more and more interest and support as a promising renewable resource to replace part of the energy supply, although it is still immature compared to other renewable technologies. This work presents a complete analysis of the wave energy technology, starting with the characterisation of this global resource in which the most suitable places to be exploited are showed, and the classification of the different types of wave energy converters in according to several features. It is also described in detail each of the stages that are part in the energy conversion, that is, from the capture of the energy from the waves to the extraction of a proper electrical signal to be injected to the grid. Likewise, existing offshore energy transmission alternatives and possible layouts are described.

Contents

1. Introduction

The level of energy consumption is one of the most direct ways to measure the progress and welfare of society. It is estimated that

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global energy consumption in 2040 will be about 30% higher than the one in 2010. In 2040, electricity generation will be more than the 40% of the global energy consumption [1]. Given that traditional energy sources are finite, this demand could not be supplied in the near future. In this context, renewable energies play a key role.

In the past three decades, great efforts have been made in the development of solar and wind energy generation. However, there is another source with high potential energy that is slowly beginning to establish itself and arouse a great interest from the scientific community, this is the wave energy.

Contrary to what one might think, wave energy is not new, it has been discussed for centuries, but until today little importance has been given to it (financial support). Early indications were found in China, in the thirteenth century, where the waves were already used to move the mills. However, the first patent was not obtained until 1799 by Girard and son in France [2].

The french Praceique-Bochaux developed in 1910 one of the first applications using wave energy to supply his home in Royan by electricity. He used a pneumatic system, similar to what is now known as OWC (Oscillating Water Column). Yoshio Masuda, from Japan, developed the whole concept of OWC holding works since 1940 [3].

On the one hand, in Europe, driven by the oil crisis, Stephen Salter and Kjell Budal pioneered this technology starting their studies in 1973 . On the other hand, in America, Michael E. McCormick was the first academic to work with this technology. As mentioned before, due to the rising price of oil, universities and researchers began to focus their efforts on wave technology. At the end of the decade, governments as well as private entities began to assist the R&D projects, but a decade later (in 80s), the decline in oil prices caused a sharp decline in this financing [4]. This leads us to today, as before, due the energy crisis and environmental awareness, this technology re-emerges stronger than ever.

This work presents a complete review of the wave energy technology describing, analysing and fixing many of the concepts that are necessary to achieve an important global knowledge of this matter. Thus, the global dispersion of this resource as well as the locations with the highest potential are introduced. Also the different developed devices for the extraction of this energy are classified. From a somewhat more technical point of view, the different energy conversion stages which are done until to get an appropriate electric signal at the output of the device are analysed. In the same way, the alternatives of that electric energy transmission, as well as the different topologies or layouts for wave parks are described.

2. Global wave energy resource

Wave energy power is enormous and more reliable than other renewable resources such as solar and wind energy; because its density (2–3 kW/m^2) is greater (wind 0.4–0.6 kW/m^2; solar 0.1–0.2 kW/m^2) [5]. Other benefits are listed below:

- Waves can travel large distances with little energy loss. For example the storms originated from western side of the Atlantic Ocean will travel to the western coast of Europe with little energy loss [2,6].
- Wave energy converters can generate power up to the 90% of the time (20–30% for wind and solar devices) [6,7].
- Its predictive capacity is far greater than the wind one [5,6].
- It has good correlation between resource and demand, since around 37% of the population of the world lives at 90 km of the coast [5].
- It is a widely available energy source because it has multiple locations (from shoreline to deep waters) [5]; example of that could be Mutriku OWC wave-plant [8] which is located in a dyke on shoreline, or the Wave Hub test-site [9] which is located 15 km from shore. Nowadays there are not offshore wave-plants installed, but there are several WECs (Wave Energy Converter) developed to be located offshore such as Wave Dragon [10], Pelamis [11] or OE Buoy [12].
- It has little environmental interference; and in the same way it can muffle the surf in port or erodible areas [2,5,6].

On the other hand, it should not be forgotten the challenges that this technology need to overcome to become commercially competitive in the global energy market:

- The conversion of the slow (about 0.1 Hz), random and the oscillatory motion of waves into useful motion to connect a generator (50 Hz) and provide a suitable output to the grid. To achieve it, some energy conversion stages are necessary, firstly to convert wave energy to electricity; and secondly, to rise WECs generated voltage levels to provide the energy transmission from the sea to the land [2,6,13].
- Waves vary in high and period, so their power level varies in the same way. This energy vector must be converted into smooth electrical signal, hence, some types of energy storage systems usually help to provide a regular power output (water reservoirs in overtopping devices, gas accumulators in high-pressure hydraulic circuits, large electrical capacitors and fly-wheels), as well as other means of compensation [2,13].
- In offshore zones, wave direction varies very often, and therefore, in order to capture as much energy as possible, the devices have to align themselves (much as the moorings leave them) with the direction. In near shore, directions can be determined in advance [6].
- Another challenge relates to offshore converters. In these locations, the device also has to withstand extreme wave conditions, which leads to difficult structural engineering challenges [13]; obviously that the maintenance operations become very difficult.
- Another important barrier is the funding [5]. Waves are an energy source with great potential and with a number of advantages that, as has been seen, make them really attractive. However, it has to compete against more mature technologies where the investment already is done. In this situation, investors should see a significant advantage to spend large amounts of money, as these plants require large investments. Moreover, in the context of the economical crisis that we live, the investment in these technologies becomes more difficult. Therefore, while this situation lasts, the "only" thing that the scientific community can do is to join the efforts in order to turn this technology into a more viable, efficient and affordable one.

For the development of wave energy technology and the selection of suitable sites for wave farms, it is necessary the knowledge of the available wave climate and power estimation. In this regard, several papers have been published which show the existing wave power worldwide. Example of that, among others, are the works presented in [14–18]; where the best quality wave model data combined with high precision satellite altimetry and measured buoy data are employed during 10 years to generate a wave atlas, such as the one showed in Fig. 1 [14]. From all these works, he following conclusions can be drawn:

- The most energy-rich areas are between 40° and 60° in both hemispheres. But, if Northern Hemisphere (NH) and Southern Hemisphere (SH) are compared, the highest mean annual wave

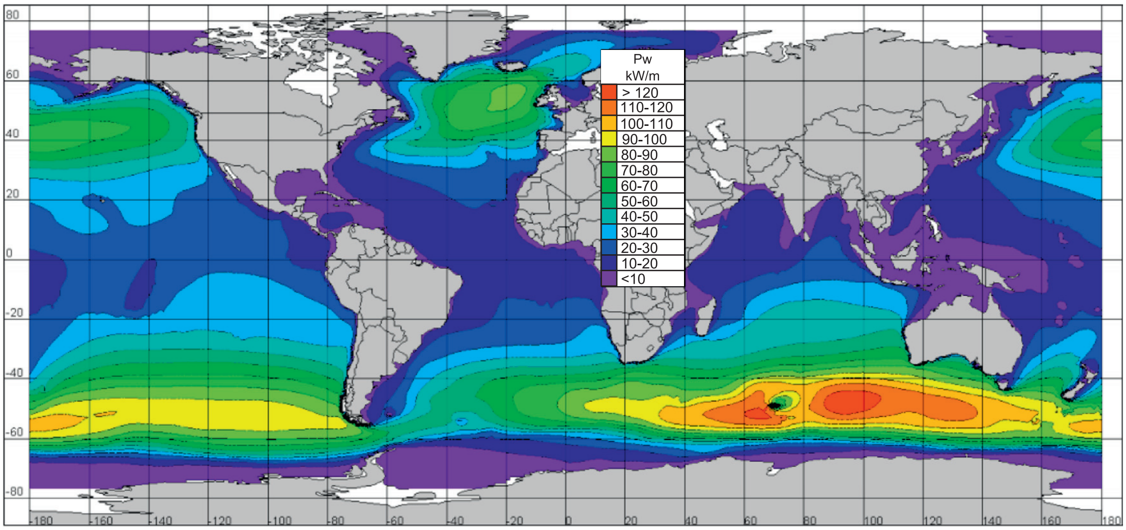


Fig. 1. Global annual mean wave power estimation in kW/m spanning 10 years period.

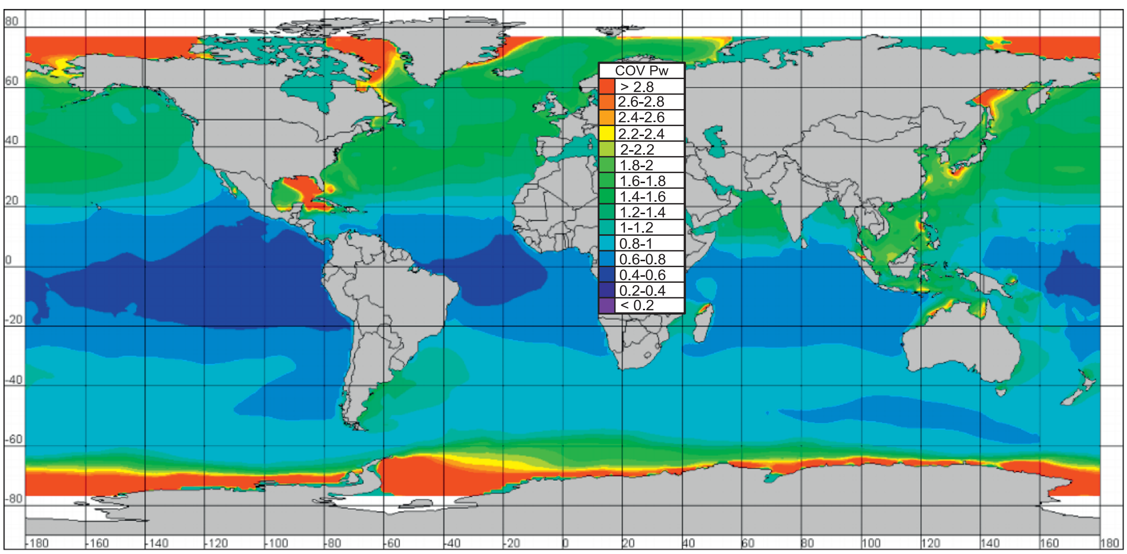


Fig. 2. The ratio of the seasonal variability of the wave energy resource, represented by COV.

power is in SH, where seasonal variations are much lower [15,16,18].

- Focusing in SH, wave energy resource is particularly larger in the South-Indian Ocean, at locations further offshore around 1400 km east of Kerguelen Island and near the southern coasts of Australia, New Zealand, South Africa and Chile; in this area the annual average power is larger than 120 kW/m [14,16,18].
- Regarding the NH, the highest values are found in the North-Atlantic zone, overall 50–60 m depth, in the west coast of British Isles, Iceland and Greenland with values between 80 and 90 kW/m, but gradually go decreasing until to 20 kW/m at approximately 20° North [18].
  In the pacific, around west coast of Canada, Washington and Oregon have good power levels too, but somewhat lower than the previous ones varying from 20 to 60 kW/m as latitude increases [18].
- The maximum global monthly power level which is similar in the two hemispheres is above 200 kW/m [15,16]. But these locations are unsuitable for any wave energy project because of the distance to shore and the surf energetic levels. For example, according to [18] the threshold at which wave power is unexploitable due to high energetic sea states is defined as four times the mean annual power; in this regard, in the North-Atlantic where the values are >80 kW/m, with the exploitability assumptions, its decrease up to 60 kW/m. In the South-Indian Ocean, it is dropped to values over 20 kW/m and, in the Pacific, reductions are about 10 kW/m. Moreover, the mean depths of wave energy test sites are around 50–60 m [15].
- On the other hand, focusing in the annual wave resource near to shore, in the NH, the highest levels are the ones registered in the west coast of the British Isles, Iceland and Greenland. In the SH, the highest energy levels are found in Southern Chile, South Africa and the entire south and south west coasts of Australia and New Zealand. Medium levels, 15–20 kW/m, are located in equatorial waters, with the highest coastal resources of Northern Peru and Ecuador, although El-Nino may induce significant inter-annual variability in this area [16].

Another important factor to define and evaluate wave energy resource is its variability. Sites with steady or moderate wave energy flux are more appropriate than sites where the resource is more energetic but unsteady, and therefore less reliable [14]. One reason is the extreme wave condition during the storms, which could damage the WECs and which is a characteristic of energetic locations; and the second one is that many WEC developers construct their prototypes working at maximum efficiency for waves within a particular range of periods and heights. So, the WEC behaviour and efficiency are good within this range, but the efficiency decreases with more variable wave conditions.

There are a lot of types of variability studies: daily, weekly, monthly and seasonal variability. However, there is also another concept to describe the temporal variability of the wave somewhere: the COV (Coefficient Of Variation) [14,18], which is obtained from the standard derivation of the power time series (σ) and the mean value (μ):

$$\mathrm{COV}(P) = \frac{\sigma(P(t))}{\mu(P(t))} \tag{1}$$

Fig. 2 [14] shows the global distribution of COV. The following conclusions have been obtained from works [14,18]:

- The NH shows a greater variability than the SH with values around 1.5 in the North Atlantic, while in the SH the index is in general less than 1 [18].
- The variability in general is smaller around the Equator in the Atlantic, Pacific and Indian Oceans, with the exceptions of Arabian Sea, the Bay of Bengal and the northern of Australia, Indonesia, Malaysia and Philippines [14].
- The greatest temporal variability occurs in the highest latitudes of both hemispheres, ice-covered sites (for portions of the year), such as Beaufort Sea, Sea of Okhotsk, the northern Bering Sea and the waters around the Greenland and Australia. However, the Recourse is also unsteady in the Gulf of Mexico and the northwestern Caribbean Sea [14,18].

Table 1 [19] shows the computed theoretical resource (in GW) based on the total gross resource (P_{gross}), the gross resource (P), excluding the contributions of $P \lesssim 5$ kW/m areas, and the net resource (P_{net}), excluding areas where $P \lesssim 5$ kW/m and ice-covered areas. It shows that the global net resource is about 3 TW.

Several authors have published detailed wave energy resource assessments of particular regions or countries, among others: Portugal [20], Baltic Sea and the Danish part of the North Sea [21], Canada [22], Spain [23], Ireland [24], Australia [25], United Kingdom [26], and United States [27]. But focusing in its wave energy resources and, looking at Table 1 and Fig. 3 it is proven that Europe, is one of the richest areas in the world, only exceeded by some parts of South America and the Antipodes. More specifically, the total wave power of the European coastline varies from 120 GW in United Kingdom, to 1 GW in Sweden, passing through 28 GW in the Gulf of Gascoigne (France), 21 GW in Ireland, 10 GW in Portugal and 3.4 GW in Denmark [28]. Likewise, Spain's several coastal areas have an enormous potential, with a wave power which often reaches 250 MWh/m [29] in Asturias, and 400 MWh/m in Galicia along the Death coast [30].

Table 1
Global and regional theoretical wave power resource (GW).

Resource	P_{gorss} (GW)	P (GW)	P_{net} (GW)
Europe (N and W)	381	371	286
Baltic Sea	15	4	1
European Russia	37	22	3
Mediterranean	75	37	37
North Atlantic Archipelagos	111	111	111
North America (E)	115	103	35
North America (W)	273	265	207
Greenland	103	99	3
Central America	180	171	171
South America (E)	206	203	202
South America (W)	325	324	324
North Africa	40	40	40
West and Middle Africa	77	77	77
Africa (S)	178	178	178
Africa (E)	133	133	127
Asia (E)	173	164	157
Asia (SE) and Melanesia	356	283	283
Asia (W and S)	100	90	84
Asiatic Russia	172	162	23
Australia and New Zealand	590	574	574
Polynesia	63	63	63
Total (GW)	**3702**	**3475**	**2985**

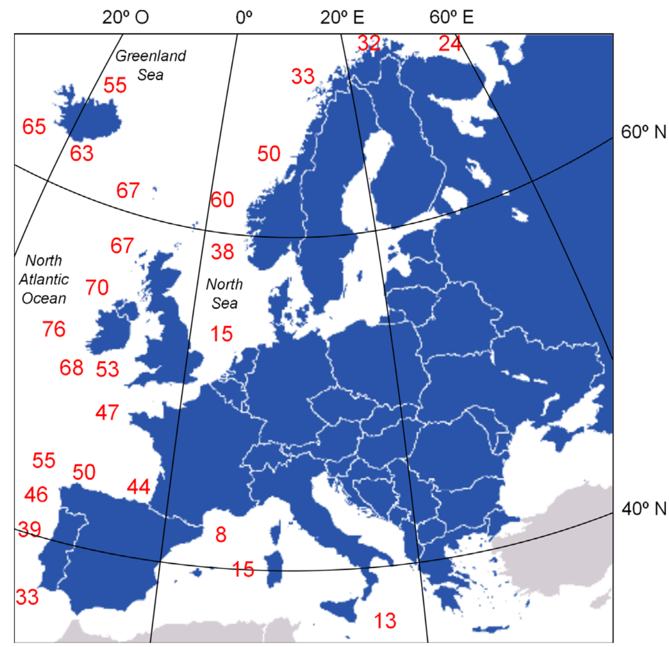


Fig. 3. European distribution of the annual wave power, in kW/m.

The Mediterranean available power resources are given in [31], and according to [28,32], for the area of the north-eastern Atlantic (including the North Sea) and for the Mediterranean side (Spain, France, Italy and Greece), the available power resources of about 290 GW and 30 GW are respectively measured. One of the best resourced area is the north-west area of the island of Sardinia (Italy), one of the most perturbed regions of the Mediterranean sea, with annual power range of 8.91–10.29 kW/m [28].

3. Wave energy converters

Over the years a wide variety of WECs have been developed, nowadays there are more than one thousand [7,33] prototypes, which, in general terms, could be classified according to three characteristics: location, size and working principle. Therefore, each WEC can be classified into several groups depending on its features. A description of each of them is presented below.

3.1. Location

As a function of the distance from the coast there are three types of converters: onshore, nearshore and offshore devices (Fig. 4, [5]). The most important aspects of each one are:

- Onshore devices: These converters are located at the shore and can be placed above the sea (in shallow water), integrated in a breakwater likes, in a dam, or fixed to a cliff. The main advantage of these converters is their easy maintenance and installation because in most cases the location is accessible. Moreover, they do not need neither mooring systems nor a long lengths of sea cable to connect the WEC to the grid. However, at the shoreline, waves contain less energy because their interaction with the seabed, and the lack of suitable land sites also causes difficulties for deploying these systems. Environmental problems could also arise, because the shore of the sea is reshaped [3,6,13].

- Nearshore devices: These converters are installed a few hundred of meters from the shore in moderate water depths (10–25 m). They usually rest on the seabed (avoiding moorings) but the structure must bear the stress that arises when the waves pass over it. In other cases, they are floating structures too [3,6,13].
- Offshore devices: These converters are located in deep waters (more than 40 m), far from the shore, and built in floating or submerged structures moored to the seabed. Due to their location, they might exploit the vast wave power of the open sea. But, in the same way, because of the open sea, the reliability and survivability of the device is a big problem, and their structure has to bear very high loads. Moreover, their maintenance is a complicated and expensive process. The long length expensive sea cables are used to carry the energy to the grid [3,6,13].

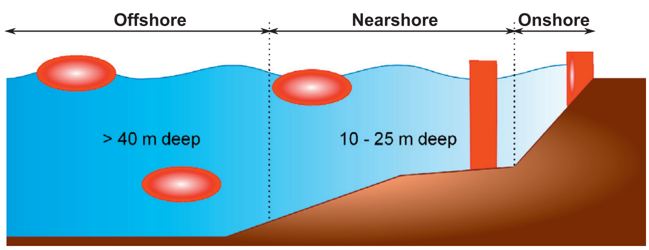


Fig. 4. Location of wave energy converters.

3.2. Device size and directional wave characteristics

According to the size and direction of the device regarding the incoming wave, WECs can be classified as follows [3,6,13,34]:

- Attenuator: These types of WECs are long structures compared with the wavelength and are placed in parallel with respect to the wave direction. In essence, they “attenuates” the amplitude of the wave. Attenuators are composed by a series of cylindrical sections linked together by flexible hinged joints that allow these individual sections to rotate relative to each other. Fig. 5 shows Pelamis 750 kW prototype converter [35] which is a typical example of this type of devices. Table 7 [36] shows principal developers of this type of WEC and their technologies.
- Point absorber: In comparison to wavelength, they usually are significantly smaller regarding to the diameter. Unlike other devices, point absorber collects the energy in all directions through its movements. These devices generate electricity from the bobbing or pitching action of a device, by converting the up-and-down pitching motion of the waves into rotary movements, or oscillatory movements (depending on specific device). Example of this is OPT's PowerBuoy 150 kW technology [37] (Fig. 5). Table 8 [36] shows the main developers of this sort of converters.
- Terminator: These devices are similar to Attenuators, as they are also long structures. However, these ones are placed perpendicular to the predominant direction of wave propagation and, in essence, “terminate” the wave action. One example

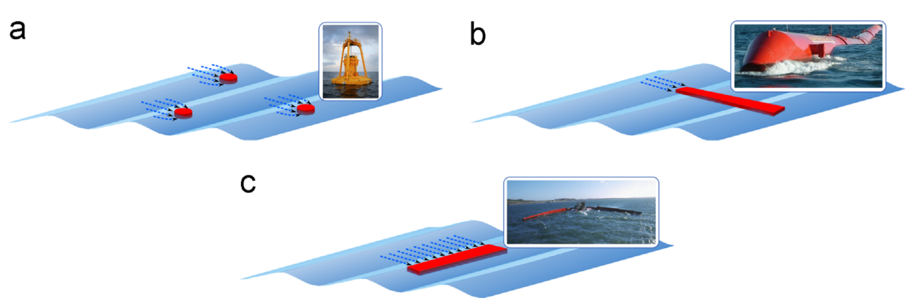


Fig. 5. Wave energy converter classification according to the size: (a) OPT point absorber, (b) Pelamis attenuator, and (c) Wave Dragon terminator.

Table 2
Offshore wave energy test sites.

Name	Location	Start date	Device scale	Distance to shore (km)	Area (km^2)	Depth (m)	Wave resource
DanWEC [52,53]	Hanstholm (Denmark)	2009	Prototype scale	0.2	1	12	16.3 kW/m
Wave Hub [9,52]	Cornwall (England)	2011	Prototype scale	16	8 (2 × 4)	50–65	> 20 kW/m
SEM-REV [52,54]	Pays de la Loire (France)	2008	Prototype real scale	15	1 (1 × 1)	35	14.4 kW/m
AMETS [52,55]	Belmullet (Ireland)	2012	Full scale	7	21	50–100	–
Runde [52,56,57]	Runde (Norway)	2009	Full scale	0.4	–	50	40–50 kW/m
Pilot zone [52]	North Sao Pedro de Moel (Portugal)	2007	–	4.5–7	320	30–90	32 kW/m
EMEC [52,58]	Orkney Isalnd (Scotland)	2004	Commercial scale	1–2	5	35–75	40 kW/m
BIMEP [52,59,60]	Basque Country (Spain)	–	Full scale	17	5.3	50–90	21 kW/m
Plocan [52,61]	Canary Island (Spain)	2011	–	–	–	50–100	–
Nissum Bredning [52,62]	Nissum Bredning (Denmark)	2003	Small scale	0.2	–	3.5–8	–
Galway Bay [52,63]	Spiddal (Ireland)	2006	Intermediate scale	2.4	0.37	21–24	3 kW/m
EMEC II [52,58]	Orkney Island (Scotland)	2011	Scaled devices	–	2	–	–
Wave Power [64]	Lysekil (Sweden)	2006	Large scale	2	–	25	3 kW/m
NNMREC [64–66]	Oregon (EEUU), planned	–	Full scale	3.2	2.6	40–50	–
HINMREC [64,67,68]	Kaneohe (Hawaii)	2003	Prototype scale	1.2	–	30	12 kW/m
HINMREC [64,67,68]	Maui (Hawaii)	2008	Commercial size	1	–	10	14 kW/m

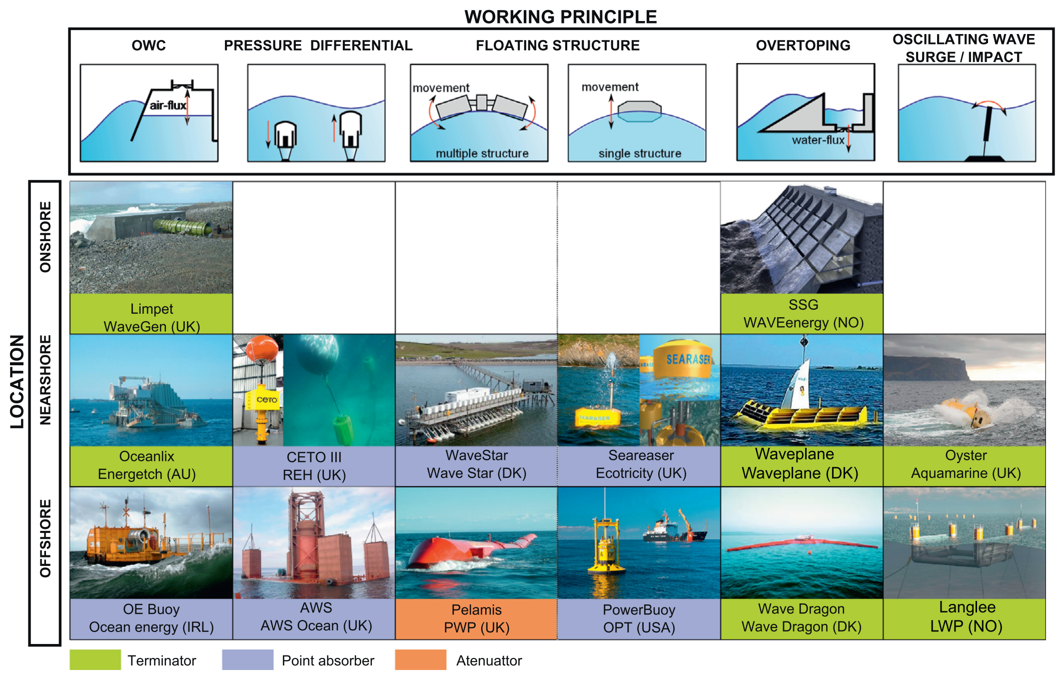


Fig. 6. Offshore wave energy test sites.

could be the WavePlane converter [38] (Fig. 5). Table 6 [36] shows principal developers of this type of device.

3.3. *Working principle*

Another classification of devices based in their working principle is presented below [3,6,34]:

- Pressure differential: Devices belonging to this category can be subdivided in two subcategories: Archimedes effect converters and OWCs. The former is a submerged point absorber typically located near shore and fixed to the seabed; it uses the pressure difference generated between the wave crests and troughs over the device. When the crest of the wave is over the device, this water pressure compresses the air that is inside of it and move the device down. If is the through over the device, the water pressure will be reduced and the device rises. A classical example of this type of converter is the 250 kW Archimides Wave Swing (AWS) [39,40], which is classified in function of its features in Fig. 6.
  The later, is usually located on the shore line or near shore, but it is based on the same principle as the previous one. Using a semi-submerged chamber open at the bottom, the reciprocating movement of the waves raises and lowers the level of water therein, moving the internal air volume. This air flow drives a turbine which rotates always in the same direction even though the air flow is bidirectional. Examples of this technology could be found in the Limpet 500 kW power plant [41] (Fig. 6) as shore line fixed structure and Oceanlix 500 kW project [42] (Fig. 6) as near shore structure. Table 3 shows some developers of this technology.
- Floating structures: This type of devices are based on a floating body which is moved by the waves. The usable oscillatory movement may be vertical, horizontal, pitch or a combination of them. Moreover, this movement can be induced either by an absolute motion between the floating body and an external fixed reference or on two or more bodies. Examples are the Searaser WEC [43] as single floating structure, and WaveStar as multiple floating structure [44–46] (Fig. 6).
- Overtopping devices: These converters are those in which waves affect a structure which increases its potential energy, kinetic, or both. Overtopping systems force water to pass over the structure, that is, a reservoir above the sea level, and then releases the water back to sea through turbines. A typical of such converter are the Wave Dragon 4–10 MW depending on how energetic the wave climate is at the deployment site [10,47] and the SSG Wave energy converter (150 kW pilot project in the island of Kvitsoy, Norway) [48]

Table 3
OWC technology developers.

Company	Technology	Country base
Dresser-Rand	HydroAir	USA
Ecole Centrale de Nantes	SEAREV	France
Energias de Portugal	Foz do Douro breakwater	Portugal
Fobox AS	FO3	Norway
Grays Harbor Ocean Energy Company	Titan Platform	USA
HydroGen	HydroGen 10	France
Instituto Superior Tecnico	Pico OWC	Portugal
Leancon Wave Energy	Multi Absorbing Wave Energy Convertor (MAWEC)	Denmark
New Energy Solutions LLC	Oscillating Cascade Power System (OCPS)	USA
Oceanlinx	GreenWAVE / BlueWAVE	Australia
OREConn	MRC 1000	UK
RWE nPower renewables	OWC	Germany
Ocean Energy Ltd	Ocean Energy Buoy	
Renewable Energy Pumps	Wave Water Pump (WWP)	USA
SeWave Ltd	OWC	Faroe Islands
Straum AS	OWC	Norway
Union Electrica Fenosa of Spain	OWC	Spain
Voith Hydro Wavegen	Limpet	UK
Wave Energy Centre (WaVEC)	Pico plant	Portugal

(Fig. 6). Table 6 shows some of the companies developing this technology.

- Impact devices: These converters are articulated or flexible structures positioned perpendicular to the wave direction. In this way, the deplector moves back and forth due to wave impact. An example is the Aquamarine Power Oyster 800 kW [49]. Fig. 6 shows this device in function of its characteristics, and Table 5 shows some of the companies developing this technology.

It can be said that there is a large number and variety of wave energy converters which vary in technological concept and design. The above mentioned Tables (Tables 3–10) present the 157 worldwide WEC concepts which are known by European Marine Equipment Council (EMEC [36]). However, as it has been mentioned. according to [33] there were more than one thousand patents in 2009. As it can be seen, more than the 50% of those 157 innovations are located in Europe (Fig. 8), where the main developer country is United Kingdom.

Some concepts are more advanced than others, in terms of the complexity of technology and in terms of development progress until today. In general, as noted above, these devices are in early stages compared to other renewable technologies (solar, wind) and compared with conventional fossil plants, and most importantly, there is still no design outweighing over the rest. Some prototypes have been built on a large scale, and have been tested in actual sea conditions, but none of them has been completed yet commercially. However there is a tendency (Fig. 7) by companies to develop more point absorber type of converters; It may indicate that it is less complex and expensive than other technologies.

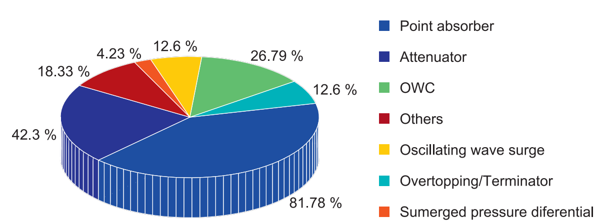


Fig. 7. Wave energy converter development %.

Table 4
Submerged pressure differential technology developers.

Company	Technology	Country base
College of the North Atlantic	SARAH Pump	Canada
GEdwardCook	Syphon Wave Generator	USA
M3 Wave, LLC	DMP Device	USA
SeaNergy	SeaNergy	Israel

Table 5
Oscillating Wave Surge Converter technology developers.

Company	Technology	Country base
Aquamarine Power	Oyster	UK
AW Energy	Waveroller	Finland
BioPower Systems Pty Ltd	BioWave	Australia
Daedalus Informatics Ltd	Wave Energy Conversion Activator	Greece
Langlee Wave Power	Langlee System	Norway
Offshore Wave Energy Ltd	OWEL WEC	UK
SDE	SDE	Israel
Yu Energy Corp	Yu Oscillating Generator (YOG)	USA
Neptune Renewable Energy Ltd	Triton	UK

Table 6
Overtopping/Terminator.

Company	Technology	Country base
Inerjy	WaveTORK	USA
JAMSTEC	Mighty Whale	Japan
Jospa Ltd	Irish Tube Compressor, (ITC)	Ireland
Kinetic Wave Power	PowerGin	USA
Ocean Wave and Wind Energy (OWWE)	OWWE-Rig	Norway
Portsmouth Innovation Ltd	Wavestore	UK
Wave Dragon	Wave Dragon	Wales/Denmark
Wave Energy AS	Seawave Slot-Cone Generator	Norway
WavePlane Production	Wave Plane	Denmark

Table 7
Attenuator technology developers.

Company	Technology	Country base
AlbaTERN	Squid	UK
Bourne Energy	OceanStar ocean power system	USA
C-Wave	C-Wave	UK
DEXA WAVE	DEXA WAVE	Denmark
Energy Aps	Convertor	
Ecomerit Technologies	Centipod	USA
Edinburgh University	Sloped IPS Buoy	UK
Floating Power Plant A/S	Poseidon's Organ	Denmark
Fred Olsen Ltd	The B1 Buoy	Norway
GEdwardCook	Floating Wave Generator	USA
Green Ocean Energy Ltd	Wave Treader/ Ocean Treader	UK
Greencat Renewables	Wave Turbine	UK
Group SM Ghouse	Free Floating Wave Energy Convertor (FFWEC)	India
Hydam Technology	McCabe Wave Pump	Ireland
Kneider Innovations	Wave Energy Propulsion	France
Martifer Energia	FLOW	Portugal
Navatek Ltd	Navatek WEC	USA
Oceantec Energias Marinas, S.L.	Oceantech Energy Convertor	Spain
Pelamis Wave Power	Pelamis	UK
PerpetuWave Power Pty Ltd	Hybrid Float	CA/USE
Pontoon Power	Pontoon Power Convertor	Norway
Ryokuseisha	WAG Buoy	Japan
Sea Power Ltd	Sea Power Platform	Ireland
T Sampath Kumar	Rock n Roll	India
Tecnalia	PSE-MAR	Spain
University of Edinburgh	Salter's Duck	N.A.
Vigor Wave Energy AB	Vigor Wave Energy Converter	Sweden
Vortex Oscillation Technology Ltd	Vortex oscillation	Russia
Wave Power Group	Salter Duck, Sloped IPS	UK
Waveberg Development	Waveberg	USA
WavePiston	WavePiston	Denmark

In a more precise, MEM (Marine Energy Matters) [50] has published a study which is based on an assessment of Technology Readiness Levels (TRL). MEM defines seven stages of maturity from concept prototype, until it is certified for its marketing:

- TRL1: Concept released.
- TRL2: Concept validated by a university or engineering research organisation.
- TRL3: Tank testing (scale device).
- TRL4: Location testing (scale device).

Table 8
Point absorber technology developers.

Company	Technology	Country base
Able Technologies L.L.C	Electric Generating Wave Pipe	USA
AeroVironment Inc	eel Grass	USA
Applied Technologies Company Ltd	Float Wave Electric Power Station	Russia
Aqua-Magnetics Inc	Electric Buoy	USA
Arlas Invest	TUVALU	Spain
Atmocean	Atmocean	USA
AWS Ocean Energy	Archimedes Wave Swing	UK
Balkee Tide and Wave Electricity Generator	TWPEG	Mauritius
Brandl Motor	Brandl Generator	Germany
Carnegie Wave Energy Ltd	CETO	Australia
Columbia Power Technologies	Direct Drive Permanent Magnet Linear Generator Buoy/ Permanent Magnet Rack Pinion Generator Buoy/Contact-less Force Transmission Generator Buoy	USA
CorPower Ocean	CorPower Wave Energy Converter	Sweden
Dartmouth Wave Energy	SeaRaser Buoy	UK
Delbuoy	Wave Powered Desalination	USA
Ecotricity	Searaser	UK
ELGEN Wave	Horizon Platform	USA
Embley Energy	Sperboy	UK
Euro Wave Energy	Floating absorber	Norway
Float Inc	Pneumatically Stabilised Platform	USA
Fred Olsen & Co. Ghent University	SEEWEC	Norway/EU
Green Ocean Wave Energy	Ocean Wave Air Piston	USA
Hann-Ocean	Drakoo	Singapore
HidroFlot SA	Hidroflot	Spain
Hydrocap Energy	Seacap	France
Independent Natural Resources	SEADOG	USA
Indian Wave Energy Device	IWAVE	India
Interproject Service (IPS) AB	IPS OWEC Buoy	Sweden
Ing Arvid Nesheim	Oscillating Device	Norway
Lancaster University	PS Frog	England
Joules Energy Efficiency Services Ltd	TETRON	Ireland
Manchester Bobber	Manchester Bobber	UK
Motor Wave	Motor Wave	Hong Kong

Table 9
Continuation of point absorber technology developers.

Company	Technology	Country base
Norwegian University of Science and Technology	CONWEC	Norway
Nautilus	Nautilus	Israel
Ocean Energy Industries Inc	WaveSurfer	USA
Ocean Harvesting Technologies	Ocean Harvester	Sweden
Ocean Motion International	OMI Combined Energy System	USA
Ocean Navitas	Aegir Dynamo	UK
Ocean Power Technologies	Power Buoy	UK/USA
Ocean Wave Energy Company	OWEC	USA
Oceanic Power	SeaHeart	Spain
Ocean Wave and Wind Energy (OWWE)	Wave Pump Rig	Norway
Pelagic Power AS	PelagicPower	Norway
Protean Energy Limited	Protean	AUS
Purenco AS	Purenco WEC	Norway
Resolute Marine Energy, Inc	Resolute WEC	USA
Seabased AB	Linear generator (Islandberg project)	Sweden
SeaVolt Technologies	Wave Rider	USA
Seawood Designs Inc	SurfPower	Canada
SEEWEC Consortium	FO3	UK
Snapper Consortium	Snapper	UK
Swell Fuel	Lever Operated Pivoting Float	USA
SyncWave	SyncWave Power Resonator	Canada
Tremont Electric	nPower WEC	USA
Trident Energy Ltd	Direct Thrust The Linear Generator	UK
Uppsala University	Uppsala/Seabased AB Wave Energy Convertor	Sweden
Wave Energy Technologies Inc	WET EnGen	Canada
Wave Energy Technology	WET-NZ	New Zealand
Wave Star Energy ApS	Wave Star	Denmark
WaveBob Limited	Wave Bob	Ireland
Waves 4 Power	WaveEL	Sweden

- TRL5: Full/large scale (100 kW) grid connected prototype.
- TRL6: Pre commercial, grid connected array.
- TRL7: Fully certified (by a recognised certification body) commercial array.

According to [50] the wave energy sector only has a 5% of developments at TRL5. The early stages of development are the simplest ones (TRL1–TRL3) because they require less capital to be carried out. The change of testing in tanks, to testing at sea (TRL5) is a much slower process, and technically more difficult and costly. There is a significant change in funding requirements between small-scale and/or tank testing devices, and between full-scale devices and sea trials with network connection. Moreover, looking to the future, according to [51] the energy from initial wave energy farms has been estimated to cost between 12 p/kWh and 44 p/kWh, with central estimates for offshore wave farms in the sub-range 22 p/kWh to 25 p/kWh. As expected, these costs are higher than other forms of conventional and renewable generation. This is normal, given that wave and tidal stream energy technologies are at early stages and initial farms have limited economies of scale. However, [51] considered that there is potential to reduce costs considerably by several routes: concept design developments; detailed design optimisations; economies of scale; and learning in production, construction, installation, operation and maintenance. Design improvements are likely to be significant in the short to medium term.

To conclude this section and give a better understanding of the importance of having this energy resource, Table 2 is presented, which summarises the main wave energy test sites around the world.

4. Energy conversion stages

There is a variety of ways to take out power from the waves: pneumatically, hydraulically and mechanically. All these forms of obtaining energy are usually called Take-Off systems, and according to [69] they can be divided in several stages depending on the different conversions that occur until obtaining the correct signal for injection to the grid (Fig. 9). These stages are defined as primary conversion stage, secondary conversion stage, and the tertiary conversion stage. In the following sections all of them are

Table 10
Other technology developers.

Company	Technology	Country base
Avium A.S.	Yeti Cluster System	Turkey
Caley Ocean Systems	Wave Plane	UK/Denmark
Ecofys	Wave Rotor	Netherlands
Eco Wave Power	Wave Clapper/Power Wing	Israel
ETYMOL	ETYMOL	Chile
Greenheat Systems Ltd	Gentec WaTS	UK
GyroWaveGen	GyroWaveGen	USA
Intentium AS	Intentium Offshore Wave Energy Convertor	Norway
Jospa Ltd	Irish Tube Compressor (ITC)	Ireland
Muroran Institute of Technology	Pendulor	Japan
Neptune Systems	MHD Neptune	Netherlands
Nodding Beam Power	Nodding Beam	UK
Ocean Wavemaster Ltd	Wave Master	UK
Offshore Islands Ltd	Wave Catcher	USA
Sea Power International AB	Streamturbine	Sweden
Sara Ltd	MHD Wave Energy Conversion (MWEC)	USA
Sieber Energy Inc	SieWave	Canada
SRI International	Generator utilising patented electroactive polymer artificial muscle (EMPAMT) technology	USA
Wavemill Energy	Wavemill	Canada
Weptos	Weptos	Denmark
WindWavesAndSun	WaveBlanket	USA
Checkmate Seaenergy UK Ltd	Anaconda	UK
Wello OY	Penguin	Finland

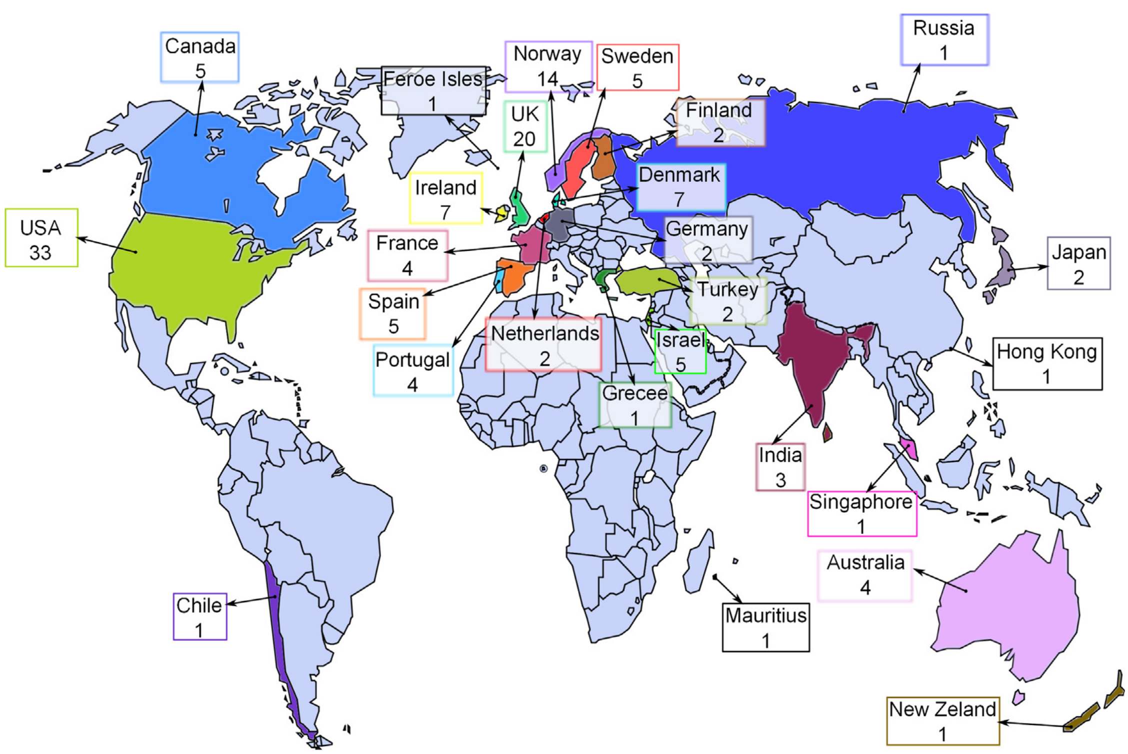


Fig. 8. Geography of WEC innovations according to [36].

described including the direct conversion stage which usually employs linear generators instead rotatory generators, and jumps from the first stage to the third one without passing the second step.

4.1. Primary conversion

This stage involves the conversion of wave motion in a body movement, an air-flow or water-flow through pneumatic, hydraulic

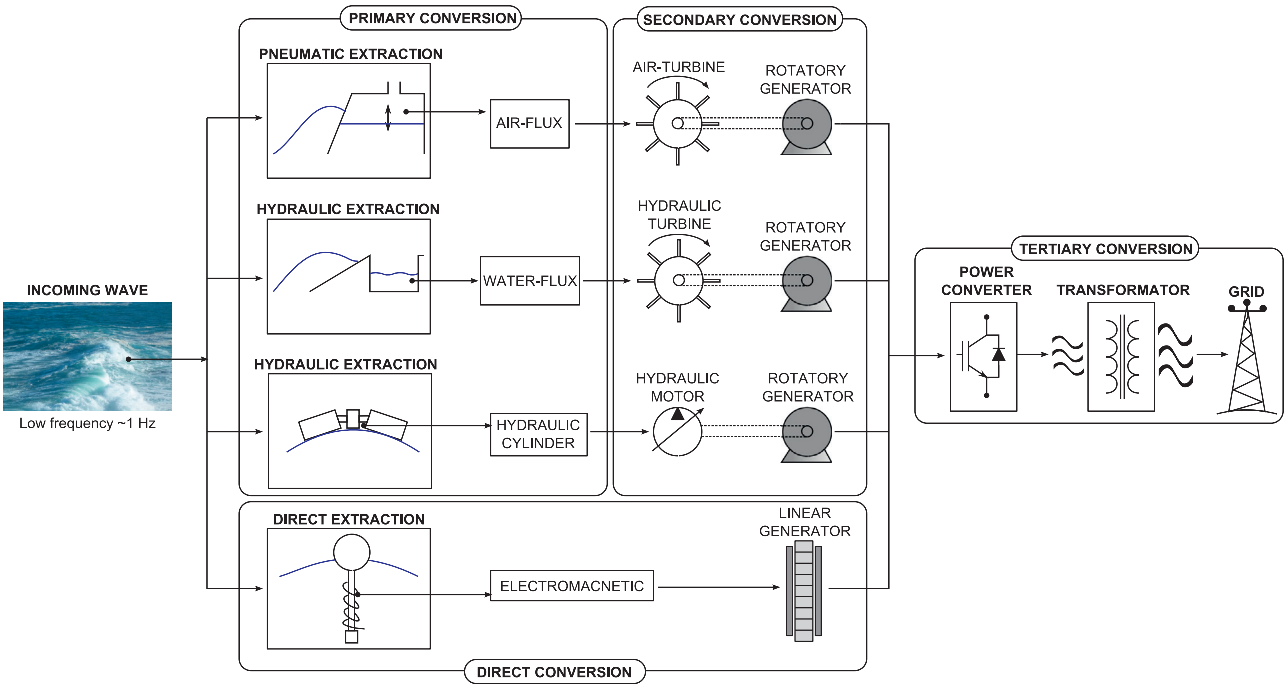


Fig. 9. Energy conversion stages.

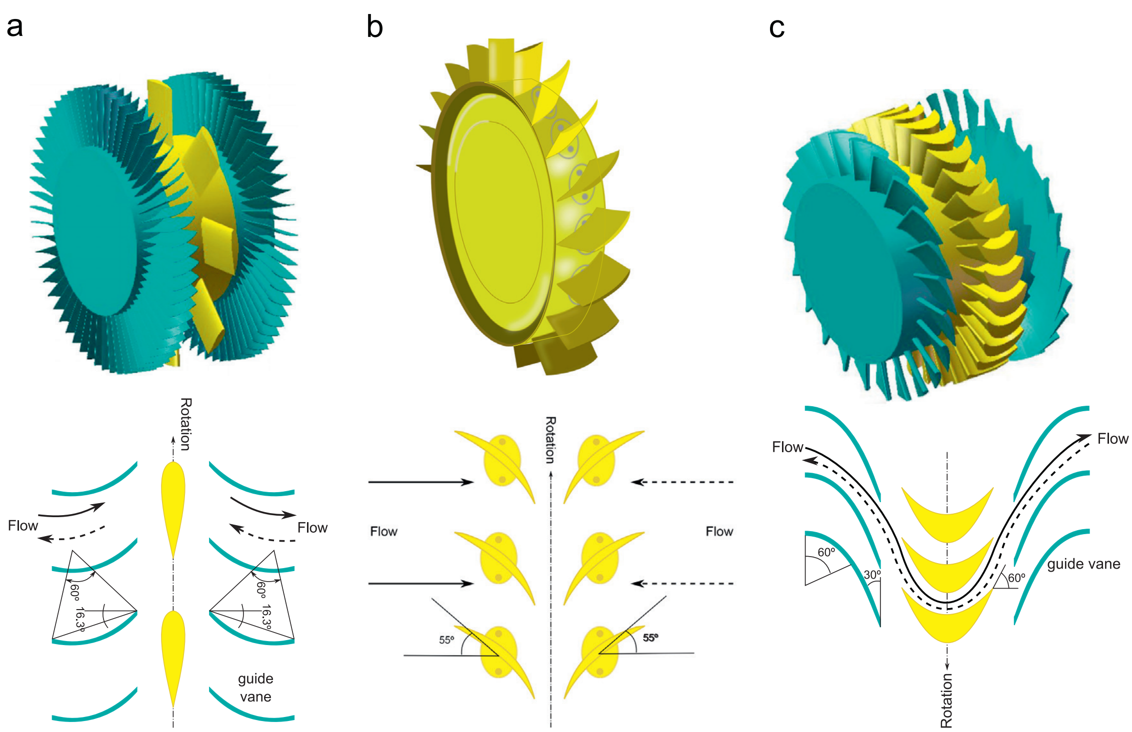


Fig. 10. Air turbines for WECs. (a) Wells turbine, (b) Denniss–Auld turbine and (c) impulse turbine.

or mechanical systems [6,69]. The aim is convert the low frequency oscillatory motion of the waves (~1 Hz) in a quick motion. To achieve this target the horizontal movements of the wave by float or fixed structures can be used; the water oscillation due to waves (within a semi-submerged structure) which can be exploited by mechanical or pneumatic systems. And the variation in pressure caused by waves below the water surface and in fixed devices, which have a tube with a lower opening (oriented in the direction of propagation of the wave) usually venturi type, to increase the speed of the work-flow.

4.2. *Secondary conversion*

This stage involves the conversion of energy from the working fluid that is generated in the previous step, into useful energy, normally electricity. The elements used for this are pneumatic and hydraulic turbines and electrical generators. A conversion of low rotation speeds or reciprocal movements to a higher rpm (1500 rpm) is achieved through these intermediate elements. In the following some of these power elements will be described in detail:

4.2.1. *Air-turbines*

Because reciprocating the air flow of the WECs, conventional air turbines (unidirectional turbines) are not appropriate in these devices. In the past, this problem was solved employing rectifying valve-systems to correct the flow direction; nowadays self-rectifying air turbines are used. Designs illustrated in Fig. 10 are the relevant: Wells turbines, impulse turbines [70,71], and Dennis-Auld turbines [3,72,73]. Below a brief description is given for each type:

- Wells air-turbine: It was invented by Dr Alan Wells in Queen University in the mid-1970s. It is a self-rectifying axial-flow turbine, meaning that its torque is not sensitive to the direction of the air flow. It actually is the most common turbine in the OWCs (Limpet OWC [41], Mutriku OWC [8]) because of features like: its relatively high speed rotation with low velocity of air-flow, the good peak efficiency (0.7–0.8 for full sized turbine), and the relatively cheap cost. Likewise, it has a number of disadvantages: the low or negative torque for small flow rates, the noise, the relatively big size for its power, and the power output drop because aerodynamic losses at flow rates exceeding the stall-free critical value. It has also a several versions such as: Wells turbine with guide vanes, with self-pitch-controlled blades, biplane turbine with guide vanes and contra-rotating Wells turbine [70,71,73].
- Dennis-Auld air-turbine: This design was developed in Australia by Oceanlix [74] and it was installed in the Oceanlinx OWC [42]. It is a self-rectifying turbine similar to a variable pitch Wells turbine. The blades are located on the periphery of the rotor hub in a neutral position, parallel to the axial direction of the flow rather than tangential to the direction of rotation as in the Wells and Impulse turbines. The Dennis-Auld turbine has a much larger pitching range than the variable pitch Wells turbine, so it has a much greater solidity (total blade area divided by turbine sweep area) which increases the efficiency of the device [3,72,73].
- Impulse air-turbine: It was invented in 1975 by I.A. Babinsten. I t is a self-rectifying turbine with an axis of rotation aligned to the direction of an air flow. As the Wells turbine it has several versions: impulse turbine with self-pitch-controlled guide vanes, turbine with active-pitch-controlled guide vanes, with fixed guide vanes and McCormick counter-rotating turbine. An example of its utilisation is the wave energy plant of Niigata-Nishi port [75]. The advantages and disadvantages of impulse turbines compared to Wells turbines are not clear [3], and it depends on which versions of each are being compared [70,71,73].

4.2.2. *Hydraulic turbines*

This turbine technology is well established and it has been in use for many years in hydro-power generation plants. They can be classified as high head, medium head or low head machines [76] (Table 11), as a function of the turbine size. The two main types [72] are described below:

- Reaction hydro-turbine: In a reaction turbine, unlike in an impulse turbine, the nozzles that discharge the working fluid are attached to the rotor. The acceleration of the fluid leaving the nozzles produces a reaction force on the pipes, causing the rotor to move in the opposite direction to that of the fluid. The pressure of the fluid changes as it passes through the rotor blades. They must be encased to contain the water pressure, or they must be fully submerged in the water flow. The two most common types of reaction turbines are the Kaplan and Francis turbines (Fig. 11).

Table 11
Groups of reaction and impulse turbines.

Type	High head (>50 m)	Medium head (10–50 m)	Low head (<10 m)	
Impulse turbines	Pelton Multi-jet Pelton Turgo	Cross-flow Multi-jet Pelton Turgo	Cross-flow	
Reaction turbines		Francis (spiral case)	Propeller	Francis (open-flume) Kaplan

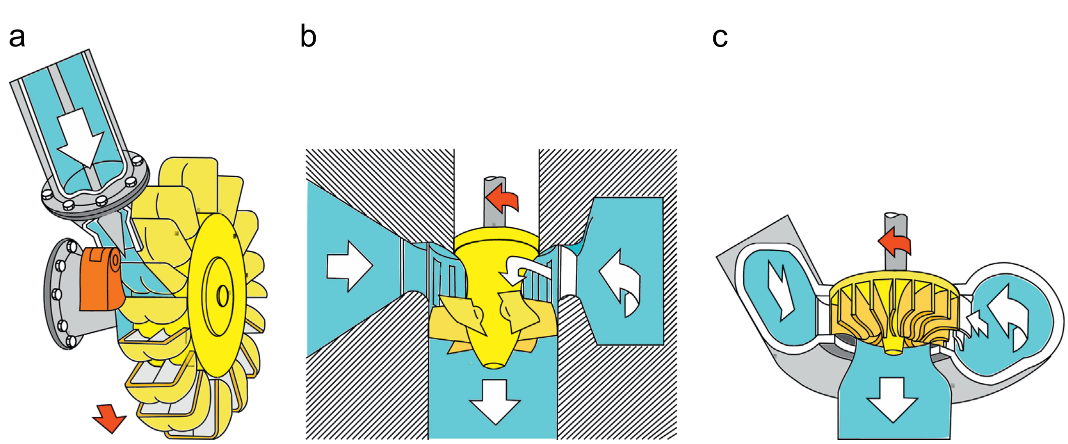


Fig. 11. Hydro turbines for WECs. (a) Pelton turbine, (b) Kaplan turbine and (c) Francis turbine.

Kaplan turbines are suited best to ocean energy devices as they can produce a highly efficient power output in low head applications, as in SSG wave energy converter [77] that uses multi-stage Kaplan turbines. The main characteristic of them is that, to achieve a good efficiency, the water needs to give some swirl before going into the turbine runner. The swirl is absorbed by the runner and the water flows straight into the draft tube with a little residual angular momentum. The swirl is produced when the water crosses several guide vanes which are mounted upstream of the runner (guide vanes can be adjusted to vary the water-flow). Another method is employ a "snail shell" for the runner. In that way, the water is going to enter tangentially and is forced to spin [76,78].
Francis turbines are suited for high head applications, therefore they are not usually employed for ocean energy applications. Francis turbine is basically a modification of Kaplan turbine in which water flows radially inwards into the runner.

- Impulse hydro-turbine: the impulse turbine is driven by high velocity water jets directed onto several curved blades mounted around a wheel. The momentum of the water jet is transferred to the turbine, so that the turbine rotates [76,78]. The most common type of impulse turbine is Pelton turbine, which is used on the Oyster WEC [49] (Fig. 11). This turbine is composed by wheel with a several split buckets set around its rim. A high velocity of water jet is directed tangentially to the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through 180° [76]. Pelton turbines are very efficient in high head and low flow applications. Therefore, they are not suitable for overtopping devices, but they are suitable for pumping prime movers, such as those in oscillating wave surge devices [76,78].

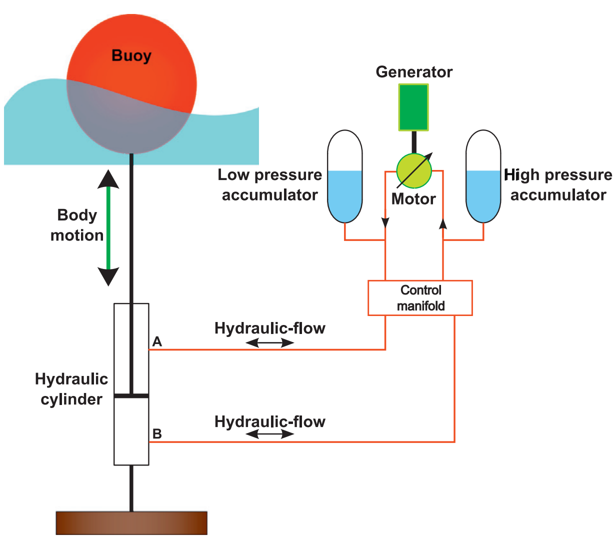


Fig. 12. Schematic representation of the hydraulic PTO.

4.2.3. High-pressure or oil-hydraulics cylinders

Another method to convert the energy is to employ a high-pressure or oil-hydraulics cylinders. These systems are used generally in slow oscillating bodies (in translation or rotation) [3], like Aquabuoy [79], Pelamis [80] or PowerBuoy [37]. The body motion is converted into hydraulic energy by a hydraulic cylinder or by various cylinders. To convert the hydraulic energy into electric energy, an ordinary electrical generator which is driven by a fast hydraulic motor is employed. To provide energy storage and to maintain a constant flow to the hydraulic motor in order to generate a regular power output, usually, between the cylinder and motor, there is a gas or oil accumulator system that stores energy over a few wave periods (Fig. 12).

4.2.4. Electrical generator

The electrical generator is a common element in energy conversion applications, and therefore in wave energy converters. It is required to convert the mechanical energy produced by the main element (turbine or mechanic interface) into electrical energy to supply the grid. The vast majority of generators are rotary, although linear generators have been developed for some wave converters. The types of machines further considered for such applications are: synchronous generators, induction generators and linear generators [55]. Leaving aside the linear generator, a comparison between different machines directly coupled to a turbine is carried out in [81,82]. These works are based in an OWC converter, but may be taken as a reference for other WECs. The generators that have been discussed are listed below:

- Doubly Fed Induction Generator (DFIG).
- Squirrel Cage Induction Generator (SCIG).

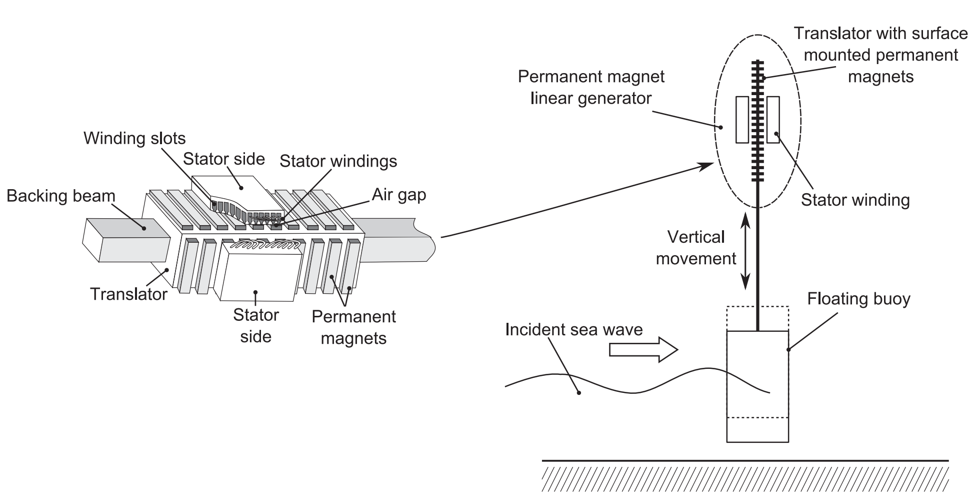


Fig. 13. Permanent magnet linear generator configuration and the mechanical system for electric power generation from sea waves.

- Permanent Magnet Synchronous Generator (PMG).
- Field Wound Synchronous Generator (SG).

These technologies are compared according to the following criteria [81,82]:

- Suitability for offshore environment: One issue to be addressed is the feasibility to use or not a machines with brushes in such environment, due the required maintenance and the need to replace brushes regularly (about twice a year).
  The DFIG generator as the SG brushes version have brushes. The maintenance of the machines is not a trivial thing, because if they are in the sea the only access is by boat, so that the working environment is not inherently stable. These considerations rule out these generators despite their advantages in terms of size, cost and efficiency.
  It should also be noted that, due to the location of the turbine, the generators are often exposed to high salt content flows. This is one of the most damaging effects in the PMG generators, since the NdFeB (type of material used in permanent magnet machines) is very sensitive to corrosion. In this regard it represents a significant disadvantage for the PMG.
- Energy efficiency: For this task it has been used a medium energy sea state. DFIG generators have not been taken into

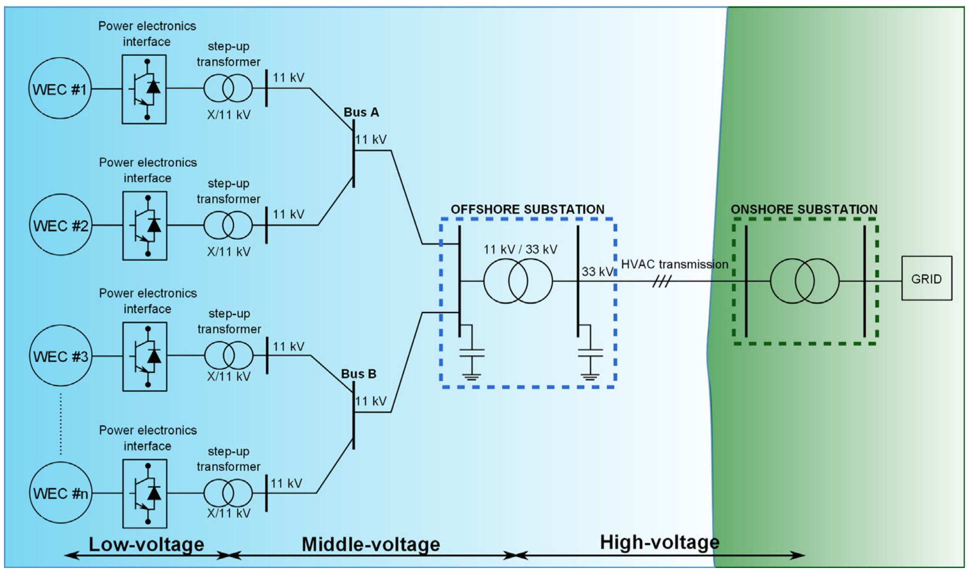


Fig. 14. Single-line diagram of an HVAC wave farm.

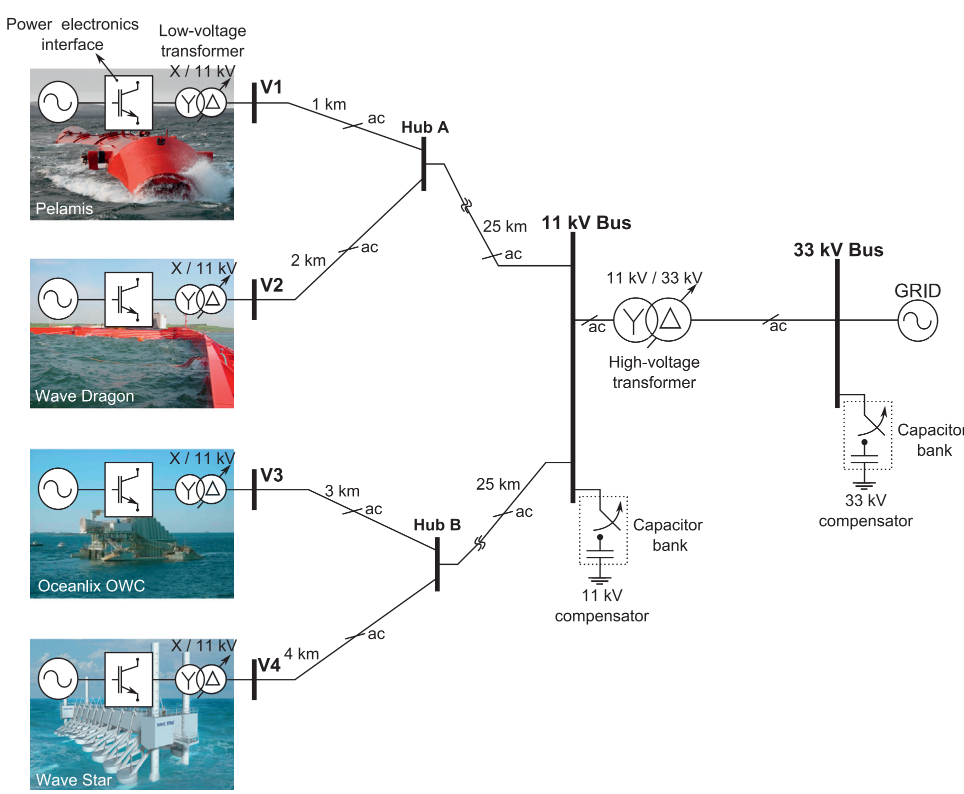


Fig. 15. Single-line diagram of the Wave Hub.

account, since they have been considered not viable at the conclusion of the previous comparison.
Attending to the results that have been taken in [81], the power output with PMG and with SG is similar, so the difference in term of efficiency between them is negligible. But the difference between these and IG generator in terms of power output is around 6–7%.

- Networking: The DFIG is at a disadvantage compared to the PMG, SCIG and SG. The stator of the DFIG is directly connected to the grid, which means that the generator is influenced more by the failures and faults in it. Also, the current peaks due to start are directly supported by the grid. The PMG, SG and SCIG are fitted with a full frequency converter between the stator and the grid, so they are more decoupled from the influence of the latter.
- Cost: a small distinction is made between IG and the SG. For power levels below 800 kW, the SG is slightly more expensive, but above that level the IG machine becomes more expensive. For PMG is difficult to set a high power cost, since many often are not manufactured for 100 kW–1 MW levels. This is one of the reasons for the high cost.

Therefore, the DFIG generator is not the best option for WECs. In terms of offshore suitability, between IG, SG and PMG generators, the last one is the worst, but it has the highest energy efficiency and its cost is dropping. The IG and SG generator have similar behaviour.

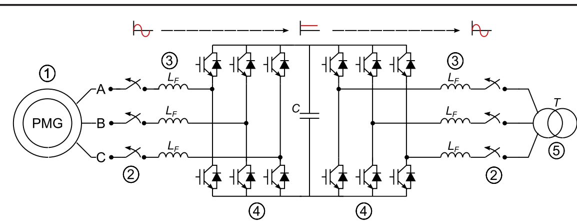
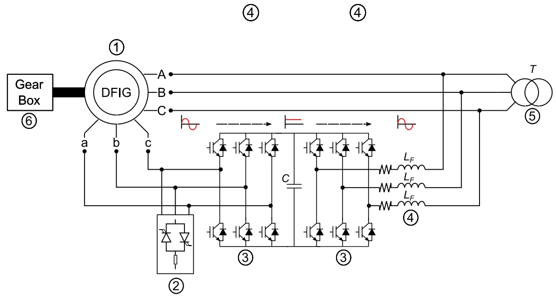
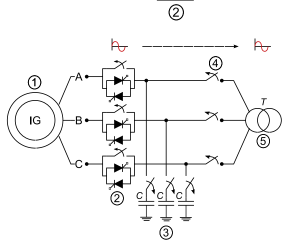
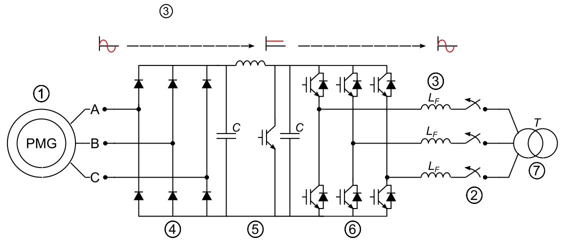
4.3. Direct conversion

In the direct conversion, linear generator is directly coupled to a vertical cylinder. The cylinder moves up and down with the incident sea wave. This topology does not need the intervention of mechanical systems; so compared with the rotational generator it is not so complex. Fig. 13 shows an example of this technology developed by [83,84]. There are three main topologies of linear electrical generators [85]:

- Longitudinal flux permanent magnet generators.
- Variable reluctance permanent magnet generators (with transverse flux permanent magnet generators as a subset of these).
- Tubular air-cored permanent magnet generators.

The major drawback of these machines is that, due to the slow speed of the waves, very large forces are needed for these devices to react; this results in physically very large machines and hence in high cost and high mass. This is because the size of a linear machine is proportional to the force capability and the force must be more than 4 metric ton to convert 30 kW of power [86].

Table 12
Commonly used power converter topologies in wave energy converter devices.

	Topology	Description
(**a**)		① Permanent magnet generator: rotatory or linear ② Main switches ③ Input and output filters ④ Input controller rectifier and output controller inverter in back-to-back configuration ⑤ Step-up transformer
(**b**)		① Double fed induction generator ② Crowbar ③ Input rectifier and output inverter in back-to-back configuration ④ Output filter ⑤ Step-up transformer ⑥ Gear box
(**c**)*		① Induction rotatory generator ② Soft start system ③ Reactive compensator ④ Main switches ⑤ Step-up transformer
(**d**)		① Permanent magnet generator: rotatory or linear ② Main switches ③ Output filters ④ Input uncontrolled rectifier; diode bridge rectifier ⑤ Shunt ⑥ Controller inverter ⑦ Step-up transformer

* This is Pelami's topology, is not the most used one, but is included because is one of the reference wave energy converters.

4.4. Tertiary conversion

This stage is the interface between the WECs and the grid, and it provides the correct power signal to inject to grid. In offshore wave farms two voltage level conversions are done, as shown in Fig. 14, where a general schematic of one HVAC wave farm is presented. In this figure, the step-up transformers, which raises the WECs output voltages to connect them to the offshore substations are shown. In this substation, the voltage level is raised in order to transmit the energy to the onshore substation.

Fig. 15 [87] shows a schematic of Wave Hub test-site; a real case. The two diagrams are similar, except that Fig. 15 has not an onshore transformer. This is because the transmission line and the grid feed-in point voltage levels are equal [88,89].

This section will concentrate on the power electronic converter which is located inside the WEC. This element allows the first voltage conversion and manages generator speed variations caused by the irregularity of the waves.

Power converters are a potentially useful technology for a wide range of applications [90–92]: transport, energy conversion, manufacturing, mining, petrochemical, etc. Within the framework of the energy conversion the electronic converter is the interface between the generator terminals and the power grid. In middle-high power applications, the most common type of electronic converter is the VSC (Voltage Source Converter) due to its controllability, modular and compact design, ease of system interface and low environmental impact.

The most commonly used topologies in wave energy converter devices are summarised in Table 12, and are described as follows:

- This topology presents an electrical generator directly coupled to a back-to-back power electronic converter. The generator could be a linear one (AWS [39,93]) or a rotatory one [94,95], but in both cases it is usually a PMG (Permanent Magnet Generator) type.
- This architecture presents a DFIG generator with gear box coupled to a back-to-back power converter with a crowbar. The crowbar is an optional element that can be included in any topology as a protection element. This configuration is often used in OWC converters [96–98].
- This configuration is implemented in the Pelamis. It employs a squirrel-cage induction generator directly connected to the grid (so it must operate at a constant speed of 1500 rpm with an allowable variation of 1–2%.), and a soft start system to reduce the inrush current during start-up. The capacitor bank is installed to supply the required reactive current to the induction machine [99].
- This topology presents a similar structure to the one shown in case (a). In this topology an AC/DC diode bridge converter is employed instead of IGBT based AC/DC converter, therefore the displacements of the generator current and voltage can not be regulated. In series with the diode bridge there is a DC/DC regulator, in which the chopper controller controls the DC link voltage that is required for DC/AC conversion [100]. The employed generator could be a linear one or a rotatory one, but anyway the topology in (a) case is the more extended one in wave energy devices.

Table 13
Output voltage level of wave energy converters.

Wave converter	Power (kW)	Output voltage (Vac)
Pelamis [99]	750	415 V/50 Hz, 690 V/60 Hz
Wave Dragon [94]	16 × 250	690 V / 50 Hz
Limpet OWC [41,101]	2 × 250	400 V/50 Hz
Mutriku OWC [102]	16 × 18.5	450 V/50 Hz
PowerBuoy [103]	150	600 V/60 Hz, 575 V/50 Hz

Nowadays, there is a greater tendency to use a 2-level VSC (2L-VSC) converters with back-to-back structure. The output voltage of these wave energy devices is not very high. It usually varies between 240 V of the Power Buoy to 690 V of the Wave Dragon (Table 13). This could be the reason for the use of a 2L-VSC converters. Normally, WECs have a step-up transformer connected to the output. This fact has two targets: on the one hand, to protect the devices from possible faults that may occur in the transmission lines or in the grid, and on the other hand, to raise the voltage level to an appropriate level for the transport and connection to the grid.

5. Power transmission systems

There are two different alternatives to transmit the generated offshore energy from the WECs to the grid: HVAC transmission (High-Voltage Alternating Current), and HVDC transmission (High-Voltage Direct Current) (Fig. 16). Likewise, the HVDC transmission has two topology options: HVDC-LCC (HVDC Line Commutated Converter) and HVDC-VSC (HVDC Voltage Source Converter). The last one has several advantages over the LCC topology:

- HVAC transmission system: This is the most employed offshore transmission system. It is a well known, stable and mature technology. When the transmission line and the grid feed-in point have the same voltage level, the transformer is not necessary [88,89]. This happens in small farms where the voltage level of the offshore farm grid is typically in the range

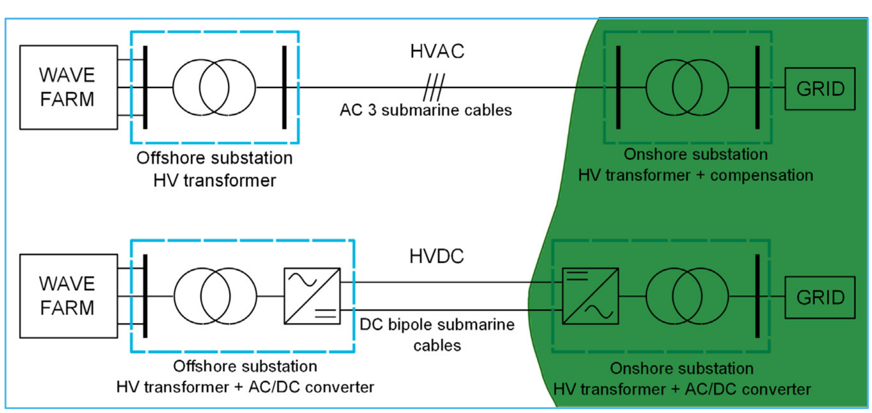


Fig. 16. Offshore transmission systems.

of 30–36 kV [104]; but in large offshore farms and/or farms with long distances to the shore, an offshore substation is necessary to step up the voltage level to 132 kV or 220 KV [105] in order to transmit energy to the shore.

In an HVAC transmission system, for the connection of a large wave farm to the onshore grid the following components are required [88,89,104] (Table 14(a)): AC collection system at the platform, offshore and onshore transformation substations with AC transformers and reactive power compensation, and three-phase submarine cables (generally cross-linked polyethylene and XLPE three conductor cables).

The offshore and onshore transformation substations are characterised by the fact that they are formed, besides by bulky transformers, by a reactive compensation systems (STATCOMs, Static Synchronous Compensator). These STATCOMs are needed in long distances because the induced reactive power increases with voltage and length of the cable; so long-transmission distances require big reactive compensation equipment [88,89,104,105]. HVAC systems use three transmission subsea cables and HVDC systems employ only two. Therefore, the losses are higher in HVDC.

Due to its construction, the distributed capacitance in the HVAC submarine cables is much greater than the distributed capacitance in airlines. Because of this and its lower cost for short distances (compared with HVDC transmission), the length of HVAC transmission is reduced for marine applications up to 50 km [88,89].

There are listed in [88,106] some offshore HVAC transmission system, for instance: Horns Rev Wind farm in Denmark, Nysted Wind farm also in Denmark, and Lillegrund wind farm in Sweden (Table 15). Despite its disadvantages, this is the most used system, because, in general terms, a large number of offshore farms do not exceed the 50 km (especially if they are a wave-farms), hence is more profitable than the other transmission systems.

According to [104], HVAC's maximum available capacity is about 800 MW at 400 kV, 380 MW at 220 kV, and 220 MW at 132 kW; all up to 100 km. They are bad cases, due the substations sizes and the subsea cable price.

- HVDC-LCC transmission system: This transmission system is the classic HVDC system based in LCCs which employs thyristors as switching elements. The main advantage is that it can transmit over long distances, and it also allows an instantaneous power control [88]. This type of transmission system requires reactive compensating capacitors or STATCOMs to compensate the reactive power demand of the grid. Because of the control angle of the thyristors the current is out of phase with the line voltage [88]. This converter has a low switching frequency range (50–60 Hz), and power losses between 1% to 2% [88,105]. This is its main drawback. This transmission system includes AC and DC filters to mitigate the high content of low-order harmonics, which are generated by LCC converters. HVDC-LCC can only transmit power between two (or more) active grids and needs an auxiliary start-system implementation. Its main components are [88,104]: transformers, the LCC thyristor based power converter, AC and DC filters, a DC current filtering reactance, capacitors or STATCOM for reactive power compensation (in one end or in the other end of the line, or both), and a DC cable.

Table 14 shows a diagram of an HVDC LCC transmission line of twelve pulses (the most extended topology).

There are a few marine installations with this transmission technology, for example to link Australia and Tasmania, and to link Italy and Greece [88]. In China it have been built the three

Table 14
Offshore energy transmission topologies.

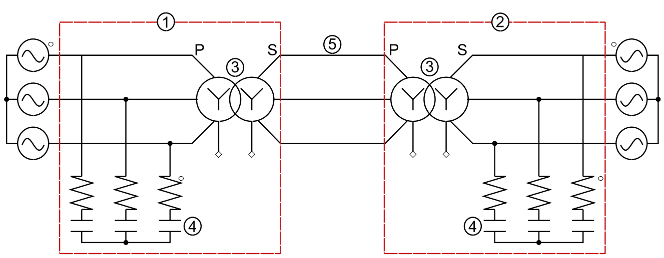
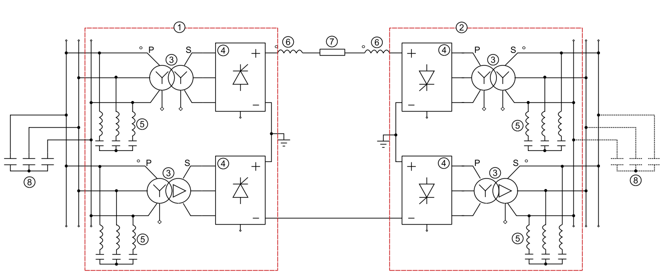
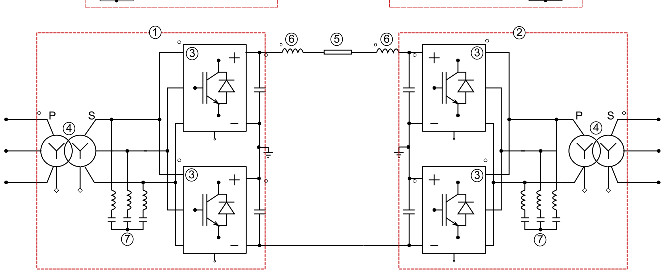
Transmission topologies	Description
	① Offshore substation ② Onshore substation ③ AC transformers ④ Reactive compensation bank ⑤ AC submarine cables
	① Offshore substation ② Onshore substation ③ AC transformers ④ Converters ⑤ AC filters ⑥ DC filters ⑦ Filtering reactance ⑧ Reactive compensation bank
	① Offshore substation ② Onshore substation ③ HVDC VSC converters ④ Transformers ⑤ Filtering reactance ⑥ DC filters ⑦ AC filters

Table 15
Offshore HVAC installations.

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Abu Safah Oil Field (Saudi Arabia)	52	50	115
Horns Rev Wind Farm (Denmark)	160	21	170
Sams Wind Farm (Denmark)	20	7.6	36
Nysted Wind Farm (Denmark)	165	55	132
Q7 Wind Farm (The Netherlands)	120	28	170
Lillegrund Wind Farm (Sweden)	110	22	145
Burbo Banks (UK)	90	40	36
Utgrunden Wind Farm (Sweden)	10	11	24
Alpha Ventus demo Wind Farm	60	66	110
Sheringham Shoal (UK)	317	22	132

Table 16
Some offshore HVDC-LCC installations.

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Basslink (Australia-Tasmania)	500	290	400
Italy–Greece HVDC link	500	163	400
The 3 Gorges-Shangai II (3GSII)	3000	976	500
The Ninggong–Shandong project	4000	1300	660
The Rio Madeira project	2×3150	2375	600

Table 17
Some offshore HVDC-VSC installations.

Project	Power (MW)	Transmission system (km)	Voltage (kV)
Cross Sound (USA)	330	40	150
Gotland Light (Sweden)	50	98	80
Tjaereborg Light (Denmark)	7.2	4.3	9
Troll A Gas Platform (Norway)	80	68	80
BARD offshore 1: Borwin 1	400	125 offshore and 75 onshore	400

Gorges-Shangai II project (3GSII), which transmits electricity from the hydro power plants in the 3 Gorges dam to the load centre in Shanghai [107], and the Ningdong–Shandong connection project, which is the first ± 660 kV HVDC transmission project in the world with 4000 MW of capacity over 1300 km [108]. Like China's projects, in Brazil there is a transmission scheme linking a new hydro power plant on the Madeira River in North-Western Brazil to the main load centres in the South-East [107] (Table 16).

- HVDC-VSC transmission system: the development of high-power devices such as IGCTs, IEGTs and IGBTs [108], have allowed the use of HVDC-VSC systems. Un that way, switching frequencies in a range of 1–2 kHz are achieved, with much lower harmonic distortion, compared with the previous systems, but with higher power losses (2–3%) in each converter [88,105,108].

  This technology allows independent transmission and total control of the active and reactive power at both ends of the line (this is not possible with LCC systems), and transmission power can be controlled with great flexibility [88,89]. For instance, on one hand, the marine energy generators at the offshore station can supply the reactive power, and on the other hand, at the onshore station, reactive power can be used to regulate voltage at the PCC (Point of Common Coupling), consequently reducing inline losses. In addition to this, the transmission distances are greater than 50 km, but not as large as in the LCC ones.

  An HVDC-VSC system has the following main components (Table 14(c)): transformers, offshore and onshore HVDC-VSC converter substations, AC and DC filters, DC current filtering reactance, and DC cable [88,104].

  The HVDC-VSC system's substation is much more compact and consequently smaller than the LCC system's conversion station (important fact for offshore applications) [88,104], and therefore less expensive. Also, HVDC-VSC system do not require an additional start-system, and it can transmit power to weak grids.

  The above mentioned advantages make HVDC-VSC transmission system more popular than the LCC. There are marine installations in USA, Sweden and Denmark [88,107]. Their features are shown in Table 17.

The HVAC submarine transmission is economically the best option with distances shorter than 50 km. But, when the transmission distance is higher, the HVDC-VSC system is the best alternative

Table 18
Offshore transmission system comparison.

Comparison element	HVAC	HDC-LCC	HVDC-VSC
Maximum available capacity per system (MW)	800	> 600	> 350
Maximum voltage level (kV)	400	> ± 500	> ± 150
Black start capability	Yes	No	Yes
Technical capability for network support	No	No	Yes
Start system	No	Yes	No
Space requirement for offshore substation	Smallest size	Biggest size	Medium size
Transmission distance	< 50 km	Longest distance (290 km)	Medium distance
Number of cables	3	2 bipolar	2 bipolar
Price	The most economical	Moderately economic	The most expensive

Table 19
Some offshore HVDC-VSC future installations.

Project	Power (MW)	Offshore distance (km)	DC voltage (kV)	Date
Atlantic Wind Connection (New Jersey–Virginia) [109,110]	4 × 1000 4 × 500	1271	320	2012-2022
MAPP (Maryland, USA) [109]	2 × 1000	244.62	640	2019–2021
Tres Amigas (Mexico) [109]	3 × 750	–	345	2014–2020
INELFE (Spain) [109]	2 × 1000	64	320	2012–2016
Canary Island (Spain) [109]	2 × 150	–	150	2012–2016
BorWin1 [111]	400	125	± 150	2012
BorWin2 [111]	800	125	300	2013
DolWin1 [111]	800	75	± 320	2013
HelWin1 [111]	576	85	259	2013
SylWin1 [111]	864	160	± 320	2014
DolWin2 [111]	900	45	± 320	2015
HelWin2 [111]	692	85	± 320	2015

in terms of efficiency although the HVDC-LCC system is the most economical (Table 18). But due the weight and size of its station, and due to the control complexity during start-up, its use is prohibited in offshore platforms [106], hence HVDC-VSC can be the best choice. Moreover, now HVDC-VSC grids are having support from private and public organisations (Table 19). In this context, some projects have been approved, such a:

- Atlantic wind connection project [109,110], where 6000 MW of wind turbine capacity will be connected to population centres and transmission node on land.
- The MAPP project (Mid Atlantic Power Pathway) is an extra-high voltage transmission line proposed to be extended from Possum Point, through Southern Maryland beneath the Chesapeake Bay and Choptank River, and crossing the lower Eastern Shore to Southern Delaware [109].
- Three Amigas project in Mexico [109] is going to interconnect the Western Electricity Coordinating Council (WECC), the Electric Reliability Council of Texas (ERCOT), and the Eastern Interconnection (crossing the Southwest Power Pool (SPP)).
- INELFE project [109] is going to link Spain and France with VSC-MMC (Modular Multilevel Converter) technology.
- Canary Island project [109] is going to link Gran Canaria and Fuerteventura islands.

On the other hand, considering the advantage of existing offshore wind-farms, there are studies that analyse the coexistence of wave parks and wind parks [45,46,105,112,113]. One of the advantages of combine both types of farms is the reduction of zero-power output hours, and the reduction of the inter-hour variability, which facilitates grid integration and makes it more reliable and predictable, and therefore less variable power is generated and transmission investment costs are reduced. The selection of the location and the variability of each resources on it (the correlation between them) is a very important issue. A suitable area for the installation of wind farms may not be suitable for wave farms and viceversa.

The collector systems or layouts of the offshore wave-farms are Another important point. The layout configurations for wave devices are based on the concepts of the existing wind-parks [114–116]. Czech et al. [117] and Balazs et al. [118] have done some studies and simulations about it.

The most used configurations for the collection and transmission of the electrical power are star layout and string layout (Fig. 17).

The main benefits of the string layout are the simplicity of its control and that it uses shorter cable lengths, which means that the cable price and losses will be lower than in those in the star layout. The major drawback is that its reliability is poorer because all the devices upstream of the point of failure must be switched off until the damaged module has been repaired. Likewise, the number of WECs which can be connected to a string is limited by the power carrying capacity of the cable [115,118]. This collector systems has been chosen in Barrow, Lillgrund, Thorntonbank-1 and Belwind-1 offshore wind farms [115].

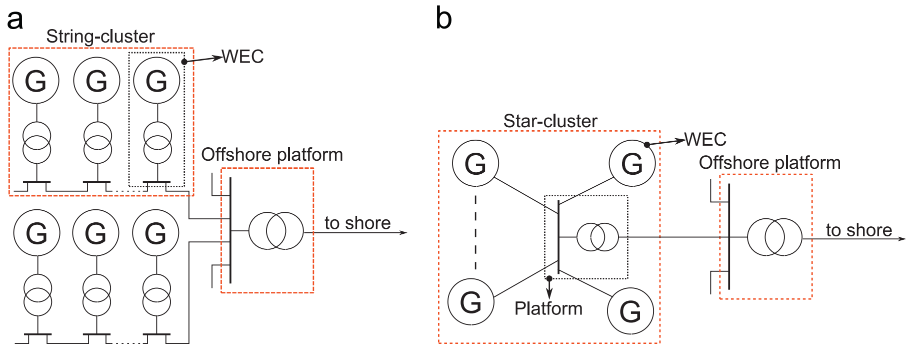


Fig. 17. Farm layout types. (a) String layout and (b) star-layout.

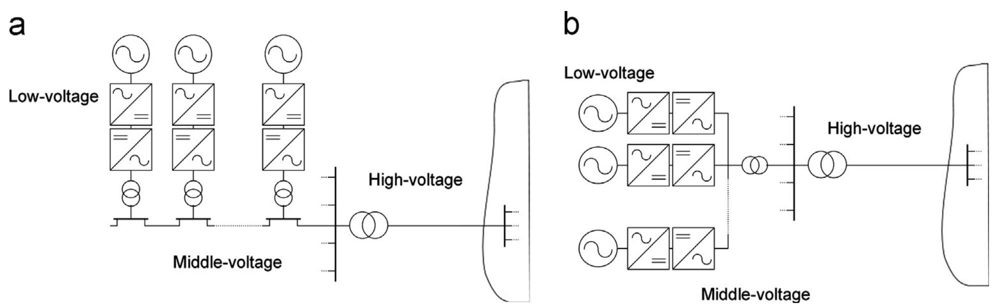


Fig. 18. String and star layouts with back-to-back converter topology. (a) String layout with back-to-back converter topology and (b) star layout with back-to-back converter topology.

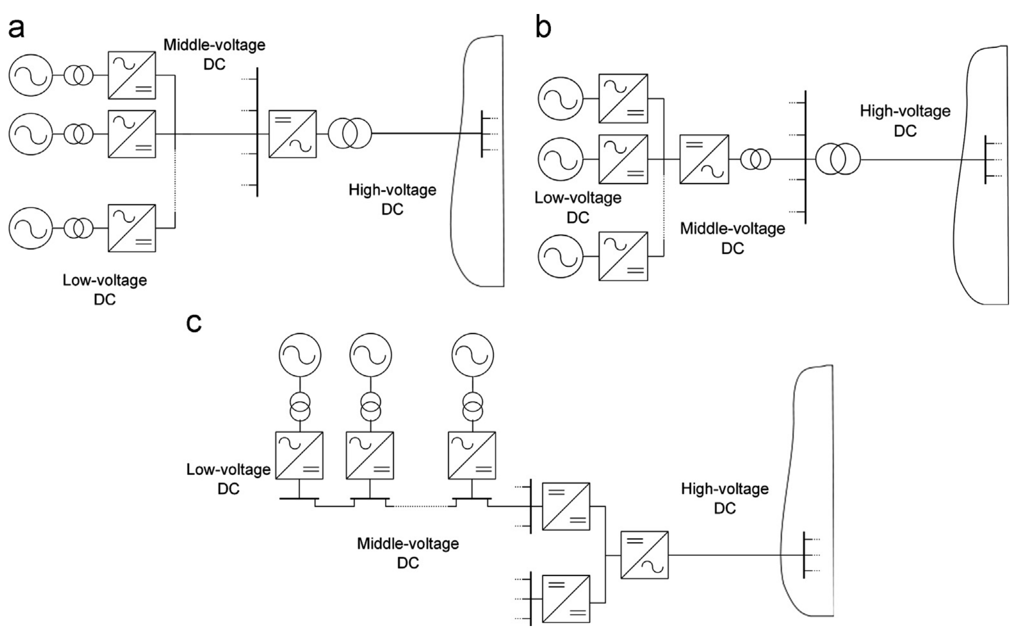


Fig. 19. String and star layouts with HVAC topology. (a) Star layout with HVAC transmission topology, (b) star layout with HVAC transmission topology and cluster terminals and (c) string and star layouts with HVAC topology, DC/DC converters and cluster terminals.

The star connection has the potential to reduce cable losses by clustering small groups of devices (WECs or wind turbines) into high voltage transformation stations (Fig. 17b). Also, it has good reliability because in case of device failure only the damaged device needs to be switched off and repaired. The major disadvantages are its price and that it needs more platforms [115,118].

In [117,118] some studies have been done about which collector system and which offshore transmission system is more suitable for wave farms. 3 MW AWS wave energy converter has been taken as a test device. These studies can be taken as a base. In them a 45 MW wave farm and a 90 MW wave farm are analysed; both with about 5 km of distance from shore:

- Collector systems with AC transmission: if AC transmission is used, depending on the farm size and distance from shore, two studies are done. The first one is an individual variable-speed farm (usually an small farms) with star and string layout and back-to-back converters (Fig. 18, [117,118]); and the second one is a farm with HVAC transmission system, that is, a large farm (Fig. 19, [117,118]).

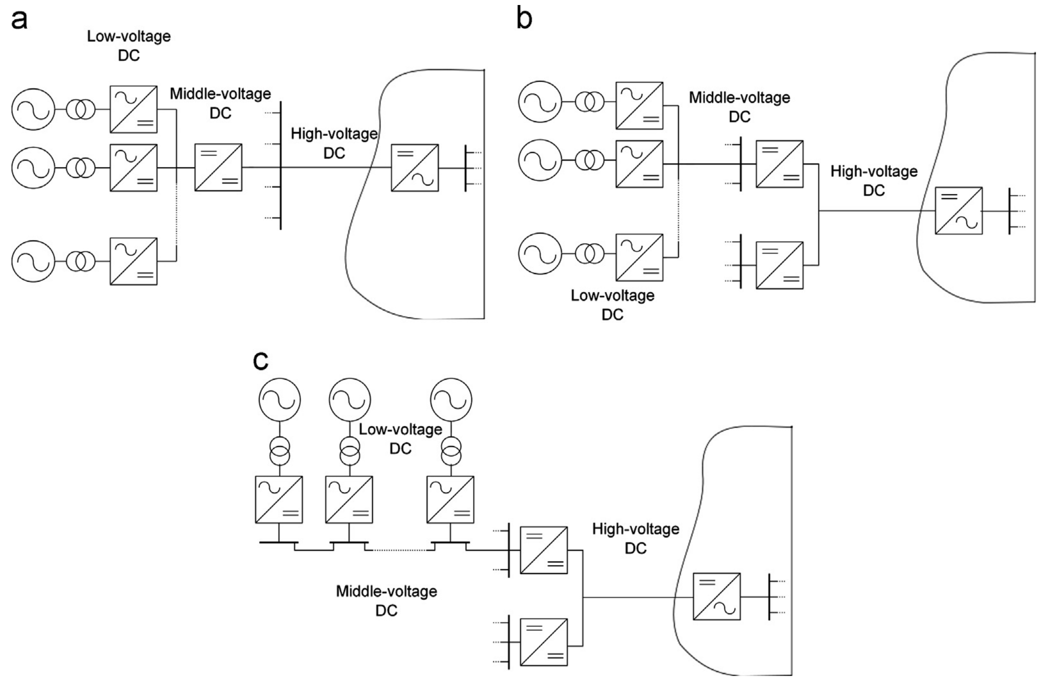


Fig. 20. String and star layouts with HVDC topology. (a) Star layout with HVDC transmission topology and cluster terminals, (b) star layout with HVDC transmission topology and DC/DC converters and (c) string and star layouts with HVDC topology, DC/DC converters and cluster terminals.

The main difference between these two layouts is the number of transformers that they use. The string layout uses generator connected transformers, and star layout, instead, only uses a cluster platform transformer. However, the string topology is cheaper than the star topology.
To perform topologies with HVAC transmission it is need to split back-to-back converters into an AC/DC converter and DC/AC converter (Fig. 19, [117,118]); therefore the number of transformers decreases. As it is shown in Fig. 19c [117,118], DC/DC transformers are also used, but according to [117,118] they can only transfer up to 50 MW power. Therefore, two of them must be connected in parallel in order to keep the park capacity at the maximum rated level. On other hand, the price of those DC/DC converters is very high and makes this topology expensive.

- Collector systems with DC transmission: in this type of transmission, as Fig. 20 [117,118] shows, there are several possibilities. In the first one (Fig. 20a, [117,118]) a cluster terminal that only requires a DC/DC converter is used. However, in the other two cases, it is necessary to connect in parallel two DC/DC converters to reach the maximum rated power.
According to the results of [117,118], in these distances from shore (about 5 km), with all these topologies, the annual energy productions and yearly losses are similar; therefore, the most important factor is the price difference. As supposed, the AC transmission with back-to-back converters is the cheapest alternative, and for these types of farms, the most appropriate. The HVDC transmission option seems unsuitable because the price of DC/DC converters are extremely high in these cases.

Although the HVDC transmission is the most economical and more efficient for distances over 50 km, the truth is that for various reasons (adverse weather conditions, survival of the devices and their complicated, costly maintenance) it is not considered for the installation of wave farms at those distances. Moreover, the installation of offshore farms is often considered for a few km from the coast (at most). In these cases (within walking distance from the coast), the best alternative is the use of an AC transmission with back-to-back converters or an HVAC, but as it has been said, the first one seems to be the most economical.

6. Conclusions

In this paper it has been presented a deep study about wave energy. The most suitable locations for exploiting this resource have been identified. They are located in the Southern Hemisphere (40°–60°), where seasonal variations are lower. Likewise, the variety of wave devices have been described and classified, noticing a slight trend of development companies (Europa covers over 50% of the development companies) to build point absorbers. However, some concepts are more advanced than others, in terms of the complexity of technology and in terms of development progress, but none of them is in marketing stage. Also, as it has been seen, the cost estimate of the wave energy is very high, but, according to some authors there are certain ways to achieve a significant reduction in the future. Likewise, the different stages of energy conversion have been described (from the capture of wave energy, until obtaining a suitable signal to be injected into the grid), as well as the elements and devices that are part of each step, like the electrical generator, that it has been demonstrated that those of DFIG type are not suitable for wave applications. In the same way, as in other renewable sources, the power converter is necessary to obtain a correct energy signal to inject to the grid. The most popular topology is the two level VSC power converter with back-to-back structure. Finally, it has been shown the different energy-transmission alternatives. Nowadays, the majority of wave and wind energy parks in operation have HVAC transmission systems, because is the most economical option for short and medium distances (<50 km). As distance increases, the more attractive option seems to be the HVDC-VSC.

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