



Wave energy: State of the art and current development

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Abstract. Currently, wave energy represents a challenge to the world's energy needs. There are innumerable prototypes and even commercial models that reveal the ability to handle the difficulties posed by the sea and obtain electrical energy. However, the implementation of these projects has shown that wave energy is not an easy resource to manipulate. In the economic aspect, the main barriers are given by the high cost of technologies in the prototype phase, as well as their operations. Regarding the technological barriers, the main ones correspond to the technological risk of the prototypes in the testing phase and the lack of specialized human capital that allows the industry to be implemented at a local level. Even so, the inventiveness and initiative of some allow them to work and face adversity with a clear objective: to take advantage of the wave power potential. In the present investigation, an exhaustive study is carried out on wave energy, its current development, techniques and technologies for its exploitation, environmental impacts, and advantages and disadvantages of the use of this renewable energy.

Keywords: Renewable energy, Wave power, Wave potential.

Energía undimotriz: Estado del arte y desarrollos actuales. Resumen: En la actualidad, la energía undimotriz representa un desafío ante la necesidad energética del mundo. Existen innumerables prototipos e incluso modelos comerciales que revelan poder manejar las dificultades propuestas por el mar y obtener energía eléctrica. No obstante, la implementación de estos proyectos ha evidenciado que la energía undimotriz no es un recurso fácil de manipular. En el aspecto económico, las principales barreras están dadas por el elevado costo de las tecnologías en fase de prototipos, así como sus operaciones. Respecto a las barreras tecnológicas, las principales se corresponden con el riesgo tecnológico de los prototipos en fase de pruebas y la falta de capital humano especializado que permita implementar la industria a nivel local. Aun así, la inventiva e iniciativa de algunos permite trabajar y enfrentar las adversidades con un objetivo claro: aprovechar el potencial undimotriz. En la presente investigación se realiza un exhaustivo estudio sobre la energía undimotriz, su desarrollo actual, técnicas y tecnologías para su explotación, impactos ambientales y ventajas y desventajas del uso de esta energía renovable.

Palabras clave: Energía renovable, Energía undimotriz, Potencial undimotriz.

Introduction

The global energy problem represents a challenge whose solution is pressing, both in economic and industrial terms, as well as in ecological and environmental terms. The consumption of fossil fuels has increased drastically throughout the world and in aggregate, the emissions of greenhouse gases (GHG) into the atmosphere. Such an effect leads to the depletion of the ozone layer, environmental pollution, an increase in global temperatures, and serious changes in climatic conditions (Wilberforce et al. 2019).

The world is currently about 1 °C warmer than it was in the pre-industrial era. This warming has caused the environmental alteration of approximately 75 % of the land and 66 % of the ocean areas, which is driving more than a million species to extinction (Ulazia et al. 2020). Scientists have warned that further increases in global temperatures could significantly worsen these effects. The latest IPCC report, "Climate Change 2021: The Physical Science Basis", provides new assessments of the chances of crossing the 1.5 °C level of warming in the coming decades and finds that unless there are immediate reductions already large scale in GHG emissions, limiting warming to about 1.5 °C or even 2 °C will be out of reach (IPCC. 2021).

In this sense, obtaining "clean" energy from the oceans is currently of international interest. Among these available ocean resources, waves claim the advantages of containing the highest energy density, being predictable and having the least visual

and environmental impact (Kamranzad & Takara. 2020), and the value attributed to said resource, by itself, is of the order of 16,000 to 18,500 TWh/year, although this varies over time and locally (Clemente et al. 2021).

Materials and Methods

Wave energy: Basic concepts and global potential distribution: Wave energy has been hailed as the most promising renewable energy source for coastal countries. Waves are formed at any point in the sea by the action of the wind; when it blows violently, they reach gigantic size and run over the sea surface at great speed, discharging all their power on the obstacles they find in their path. The effects of these shocks are enormous and the amount of energy dissipated in them is considerable (Babarit. 2017). As with other forms of renewable energy, wave energy is not evenly distributed around the planet. The global distribution of wave power levels is shown in Figure 1 where the units are given in kW/m of the wavefront.

As can be seen, the greatest potentials are shown between 30- and 60-degrees latitude, in both hemispheres. Large resources are particularly appreciated along the western coast of Europe, off the coast of Canada and the United States, and off the southern coast of Australia and South America (Khare et al. 2020).

Wave energy background: Fishermen and sailors, since ancient times, have depended on knowing the behavior of the waves; however, the statements made in this regard during the eighteenth century

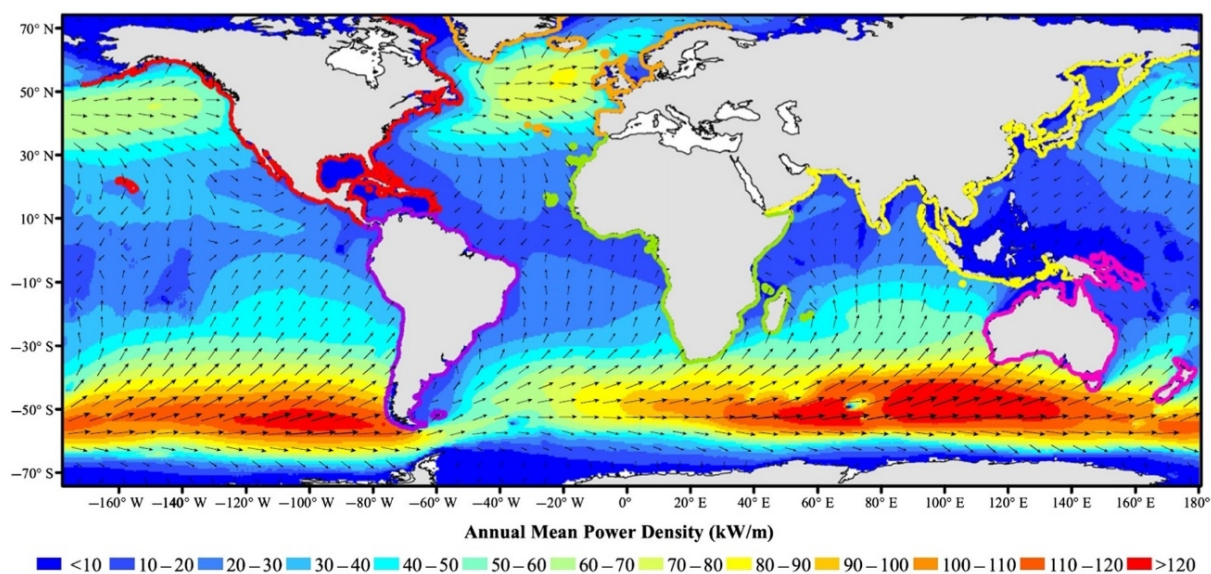


Figure 1. Annual mean wave power density and annual mean wave direction, adapted from Gunn and Stock-Williams (2012).

reflected that there was great inexperience since the rigorous study of waves was not booming until the end of World War II. In 1925, the first ideas about the process of wave formation on the sea surface were published (Rusu & Onea. 2018). In 1957, the first theories of wave formation were proposed by Phillips and Miles. These took into account the effects of nonlinearity and turbulence (Melville. 2018).

An advance of vital importance on the non-linear interaction mechanisms of the waves were the works carried out in 1967 by Hasselmann, due to their strong influence on the evolution of the frequency spectrum (De Carlo *et al.* 2020; Zakharov. 2018). In 1973, the engineer Stephen Salter, from the University of Edinburgh, presented a project known as the “Salter Duck”. This is a type of structure whose cross-section is cam-shaped, resembling a duck floating on water (Kim *et al.* 2019). In the 1940s, the Japanese naval officer Yoshio Masuda developed a navigation buoy based on an air turbine, this being the most successful invention at that time, as it provided the best solution to supply energy to the batteries of the buoys, avoiding the difficulties of having to replace them at intervals in remote oceans

(Aderinto & Li. 2018, 2019, Ahamed *et al.* 2020, Sheng. 2019; Triasdian *et al.* 2018).

More advanced research was carried out for 20 years, to finally present the LIMPET project (Land Installed Marine Powered Energy Transformer), as a result of the collaboration of Wavegen, Queen's University Belfast, and the European Union, which made it possible to install an electricity generating station with 500 kW of power taking advantage of the waves on the Scottish island Islay to provide energy to more than 400 homes and in the year 2000 it was unified with the United Kingdom's electrical system (Bozzi *et al.* 2018).

In Denmark, the Wave Dragon company has been developing since 2003 a technology prototype called Wave Dragon, built and installed on the Nissum Bredning coast. It is distinguished by being the first wave energy converter (WEC) located in the sea in the whole world, moored to the bottom and with a ballast of 237 tons (Babarit. 2017); Figure 2. Established in 2003, the EMEC (European Marine Energy Centre) is the first center of its kind in the world, offering wave and tidal energy developers, converters, and technologies capable of generating electricity by harnessing the power of both. With



Figure 2. Photograph of the Wave Dragon technology, adapted from Christensen *et al.* (2005).

purpose-designed and accredited offshore testing facilities, it was created by the United Kingdom government as part of a more ambitious project, under which renewable energy is expected to make up 20 % of national energy in the world by 2020. Beyond technology demonstration and testing, EMEC provides a wide range of consulting and research services, and is at the forefront of developing international standards for marine energy, while forging alliances with other countries and exporting its knowledge to the whole world to stimulate the development of a global industry of marine renewable sources (EMEC. 2022). In the United Kingdom, the Aquamarine Power Company developed and installed at the EMEC in the period 2005-2009, a device called Oyster 1, near Inverness, Scotland. With a power of 315 kW, that works by means of a submerged surface that oscillates with the coming and going of the waves converter oscillator type; (Babarit. 2017).

The Pelamis Wave Power Ltd. company built a device called Pelamis. This technology was successfully connected to the electricity grid in October 2010 and is currently being tested (Pelamis Wave Power. 2022).

Another specific technology is the Power Buoy from the company Ocean Power Technologies. In September 2010, they completed the first grid connection of a wave energy device in the United States at Marine Corps Base Hawaii (Wilberforce *et al.* 2019).

The interest in research on ocean renewable energies is increasing rapidly in Latin American countries such as Chile, Mexico, and Brazil; however, its progress is not comparable to that developed by China, the United States, Japan, the United Kingdom, Germany, India, New Zealand, Spain, and Denmark (Ahamed *et al.* 2020, Mishra *et al.* 2021, Rusu & Rusu. 2021). The trend, according to the experience acquired in the exploitation of other energies, reveals that as greater knowledge is achieved in the use of the resource, more reliability and lower costs will be obtained. Devices based on the oscillating water column constitute a particularly well-established technology within wave energy (Wang & Ning. 2020). The most current ones focus on achieving greater efficiency during the conversion so that it can be profitable in the future (Guillou *et al.* 2020).

The global evaluation of wave power has been the subject of several studies based on sea state conditions provided by numerical models or satellite measurements (Martinez & Iglesias. 2020). It has

indicated regional areas with high potential, but it may not provide an exact local picture of where the places with the highest concentrations of energy are located, the so-called "hot spots" (Akpınar *et al.* 2019, Belibassakis *et al.* 2018).

In recent years, numerical wave models such as WAVEWATCH-III (WW3) (Ahn *et al.* 2019) and Simulating Waves Nearshore (SWAN) (Lin *et al.* 2019), have become feasible tools to assess the potential wave energy, mainly due to its ability to produce long-term projections with high spatial and temporal resolution (Bento *et al.* 2018, Patel *et al.* 2020). Numerous researchers from the international scientific community have evaluated wave resources on a global and regional scale. Its potential has been found to be greatest (above 35 kW/m) in the northeastern parts of the North Atlantic and Pacific Oceans, the western coast of North America, the southern coast of Australia, Chile in South America, and the southwestern coast of South Africa (Patel *et al.* 2020). On a regional scale, most studies have focused on Europe, since wave heights are significant throughout the year, while others have been conducted to assess such energy in calm and closed seas such as the Baltic Sea (Jakimavičius *et al.* 2018), where the magnitude of the potential is significantly low compared to the open sea due to its limited range. Yang *et al.* (2019) evaluated wave energy resources in the North Indian Ocean based on ten years of retrospective model data and reported that the waters off Somalia and the Arabian Sea are the richest areas in energy (9-24 kW/m).

Research has also paid special attention to the implementation of wave energy technologies and devices (Medina-López *et al.* 2019, Moñino *et al.* 2018); the evaluation of the wave energy resource (Carballo *et al.* 2019, López-Ruiz *et al.* 2018a, López-Ruiz *et al.* 2018b); and the optimization of wave energy parks for coastal protection purposes (Rodríguez-Delgado *et al.* 2019).

In another study, Maurya and Singh (2020) proposed the selection of WECs based on the annual cost per MW. Nagababu *et al.* (2018) evaluated the performance of five WECs in terms of capacity factor and developed spatial maps across India's exclusive economic zone.

Wave energy harnessing techniques: Next, wave energy devices are classified according to numerous factors, given the great diversity of conversion systems:

- 1 Considering the relative position with respect to the coast

Onshore installations: the main advantage of these converters is their easy maintenance and installation because in most cases the location is accessible; however, they are exposed to wind and waves. On the other hand, they do not need mooring systems or long cables to connect to the electrical network, but the energy potential is less than offshore (Fernández Díez. 2005).

Nearshore installations: these converters are installed a few hundred meters offshore in moderate water depths (10–25 m). They usually rest on the seabed (avoiding moorings), but the structure must withstand the stress that arises when waves pass over it. In other cases, they are also floating structures (Weiss *et al.* 2018).

Offshore installations: also known as third-generation converters. They are found at depths greater than 50 m and have high energy potentials since as the distance to the coast increases, the energy density also increases. However, its accessibility and the transport of energy to the network are more complicated. Problems of installation, maintenance, anchoring, interference with maritime traffic, among others, appear. However, they are the most numerous projects (Aderinto & Li. 2018).

2 Considering the orientation or position relative to the wavefront

Totalizers or terminators: small structures compared to the incident waves. Generally, several devices are grouped following a line. They concentrate the waves in a point (Idárraga *et al.* 2018).

Attenuators: their structure is elongated and they are placed parallel to the direction of advance of the wave. They capture energy progressively. The forces on both sides of the structure are compensated, so they require a less resistant mooring system than in the case of totalizers (Idárraga *et al.* 2018).

Point absorbers: they are elongated in shape and are placed perpendicular to the direction of advance of the waves. They demand a stronger mooring system than attenuators (Al Shami *et al.* 2019).

3 Considering the way of obtaining energy

Passive or static systems: throughout the conversion process they remain immobile, generating energy with the movement of the waves (Idárraga *et al.* 2018).

Active or oscillating systems: the energy is produced by taking advantage of the relative movement between the fixed and mobile parts of the elements of the system. Two types are distinguished; in the first, the waves act directly on the moving

body; while, in the second, a water-air interface is used, so that the wave displaces the air, and this, in turn, moves the mobile body. These systems are dynamically slower, but they do not have worse performance for that (Idárraga *et al.* 2018).

Development

Wave energy converters: There are several devices in different stages of maturity (Østergaard *et al.* 2020), and some of them are found in the marine environment (Soukissian *et al.* 2020). Wave energy has remarkable potential but, unfortunately, progress in developing commercial prototypes has moved rather slowly (Maria-Arenas *et al.* 2019). Next, the main wave energy converter devices are explained, according to the classification depending on their technology readiness level (TRL):

- AWS-III (TRL 9): Developed by AWS Ocean Energy Ltd, with a maximum rated power capacity of 2400 KW (Fig. 3) (AWS-III. 2022).



Figure 3. AWS-III device, adapted from AWS-III (2022).

It consists of a multi-cell matrix of flexible membrane absorbers that converts the wave into pneumatic energy through the compression of the air within each cell. The cells are interconnected, allowing air exchange between cells in antiphase. Turbine-generator sets convert pneumatic energy into electricity. A typical device will have an array of nine cells, each approximately 16 m wide by 8 m deep, arranged around the hull structure of a catamaran. The AWS-III will be free to moor at water depths of around 100 m using standard mooring extensions (AWS-III. 2022).

- Power Buoy PB3 (TRL 8): technology developed by the company OPT (Ocean Power Technologies) of the United States. The system consists of taking advantage of the vertical and pendulum movement of the waves through a buoy of about 2 to 5 m in diameter, open at the bottom. It is installed in maritime locations with an approximate depth of 40 m. The energy is obtained through a hydraulic system that uses the relative movement between the float and the buoy mast. The method pumps a fluid (oil) at high pressure which, in turn, drives an electrical generator. The energy obtained is transmitted to the coast through a cable located on the seabed. In the case of extreme storms, it is deactivated as a precaution and once it has returned to normal, it is activated again and produces energy. This type of converter is designed to be installed in a

group, to obtain a profitable amount of energy (Power Buoy. 2022).

- CETO 6 (TRL 7): point absorption technology of 1 MW of power created by the Australian company Carnegie Clean Energy (Fig. 4). It consists of a steel buoy approximately 20 m in diameter, totally submerged and anchored to the seabed, whose movement activates a hydraulic pump. The high-pressure hydraulic fluid is used to drive an electrical generator that is located inside the buoy. Electrical energy is returned to shore via submarine cables to power desalination plants and for export to the electrical grid (CETO 6. 2022).

This device, being submerged, does not have a visual impact, and operates in deep waters far from bathers, so it does not present a danger to them (CETO 6. 2022).

- H24 (TRL 7): Created by 40South Energy Italy. A 50 kW plant, made up of 4 H24 devices for an experimental campaign, was deployed at the Marina in Pisa, Italy, in November 2015. In 2018, it delivered the first wave-produced electricity to the Italian grid. Assembled in two parts: a 12 m long guide and a mobile component that is left free to slide on it. The plant is made up of multiple modules mounted at a depth of 12 m and fixed to the seabed. The device is activated by the force of the waves that impact the mobile component and cause its relative movement concerning the guide (Mattiazzo. 2019).

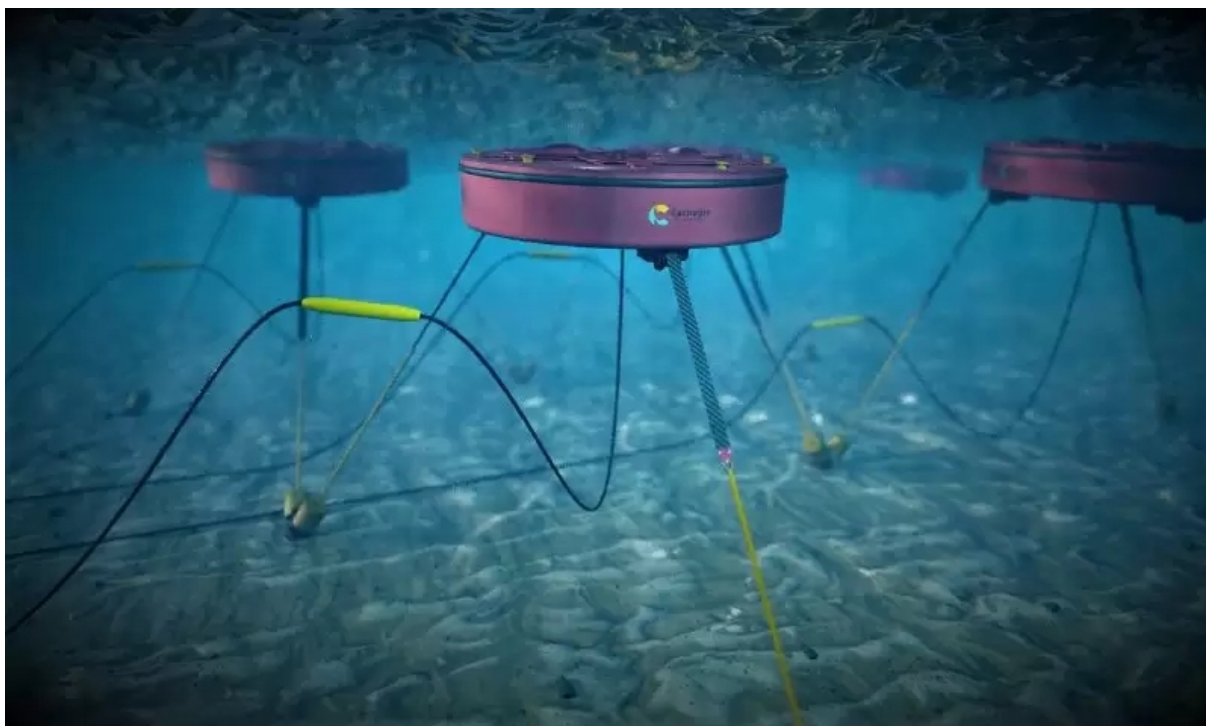


Figure 4. CETO 6 Device, adapted from CETO 6 (2022).

- ISWEC (TRL 7): created by Wave for Energy Srl, it has a nominal power of 100 kW and is located on the surface. It is based on a rotating flywheel inside a closed hull: thanks to the gyroscopic effect, the pitching movement of the float is converted into rolling oscillations and finally transformed into electrical energy. Among the main advantages of this device are high reliability, ease of accessibility, and maintenance. However, a necessary condition for energy conversion is to keep the flywheel in constant rotation, which inherently represents an element of power loss and reduces overall efficiency (Bracco *et al.* 2020, Sirigu *et al.* 2020).

- Mutriku (TRL 7) (Basque Country): located outside the Mutriku port breakwater; It consists of 16 30 kW turbines that provide a maximum power of 480 kW, generating 600 MWh/year. Its approximate cost is 5.73 million euros (Faÿ *et al.* 2018, Ibarra-Berastegi *et al.* 2018).

- Penguin (TRL 7): the first large-scale Penguin, was deployed in 2010 by the Finnish company Wello Oy and tested in the harsh conditions of the North Sea. The device had been launched 4 times and during the test period it lived up to expectations, having survived waves of more than 18 m. The trials provided valuable data and insights into the challenges of building a large-scale converter in real sea conditions, allowing the design to be refined for commercial success (Wello Oy. 2022).

- OWC Pico Azores (TRL 7): the Pico plant is located in the Azores, with an installed capacity of 400 kW and was built between 1995 and 1998, under the supervision of the Lisbon Higher Technical Institute. Various problems arose during this time due to the configuration of the plant and equipment. In 2005, the project was redesigned, and in 2009 the developers reported a total operating time of 265 hours. Most of the systems are still in the early stages of development (small scale) and only a few are being tested in marine environments to assess efficiency in terms of electricity generation and survivability (Rusu & Onea. 2018).

- Wave Clapper (TRL 7): surface technology developed in Israel by the company Eco Wave Power in 2011 with a power of 100 kW. It consists of floats that rise and fall with the ascending and descending movement of the waves. These are attached by robust arms to any type of structure (breakwater, pier) (Eco Wave Power. 2022a).

- Wave Roller (TRL 7): system designed by Finnish diver Rauno Koivusaari; there is currently a

full-scale prototype installed in Peniche (Portugal). It consists of a plate anchored to the bottom of the sea at the bottom, which oscillates due to the movement of the waves on the bottom. The kinetic energy is transmitted to a piston and is transformed into electrical energy (Morim *et al.* 2019, Samad & Suchithra. 2021).

- Wavestar WEC (TRL 7): it is a medium-scale wave energy converter. It was installed in Hanstholm, Denmark in 2009 and delivers a net power of 600 kW (Wavestar. 2022).

- Yongsoo OWC (TRL 7): oscillating water column type device created by the Korea Institute of Ocean Science and Technology. It produces a rated power of 500 kW. Its construction was completed in July 2016 and it was installed 1.5 km off the coast of Jeju Island. Equipped with impulse turbines and 250 kW generators and connected to the grid through the 22.9 KV AC submarine cable, it is currently in the testing phase. Analyzing the first performance data from the test, the maximum efficiency for the OWC chamber, turbine, and generator were found to be equal to 52.7 %, 40.0 %, and 91.7 %, respectively (Yongsoo OWC. 2022).

- LIMPET (TRL 6): it was built on the island of Islay in Hebridean, Scotland, in the late summer of 2000. LIMPET supplies power to the national grid. It consists of two Wells-type turbines, each of which has an installed capacity of 250 kW. It has proven to be structurally resistant to extreme weather conditions with minimal maintenance. Furthermore, it currently serves as an experimental base to develop new technologies (Ahamed *et al.* 2020, Samad & Suchithra. 2021).

- Neptuno 3.1 (TRL 6): Point absorber system designed by the North American company Neptune Wave LLC in 2010. It was developed to operate in shallow waters from 25 to 75 m. It has a built-in horizontal axis pendulum, is capable of producing up to 225 kW, and can take advantage of wave heights from 1 to 10 m (Neptune. 2022).

- Oyster 800 (TRL 6): It was developed and marketed by the company Aquamarine Power Ltd. in the north of Scotland. It is a semi-submerged device installed in areas with a depth between 10 and 20 m. Its mechanism is simple, and it has few moving parts that are hardly affected by adverse conditions. Its maintenance is favored by the easy access to the mechanism and the presence of the electrical system on the coast (Babarit. 2017, Mishra *et al.* 2021; Xu *et al.* 2019).

- Seabased WEC (TRL 6): 85 kW point absorber designed by Seabased AB in Sweden. It

was built to extract energy from waves of 1 - 3 m height. It is based on a buoy that transmits energy through a steel line to linear generators that rest on the seabed. The waves move the buoys, which in turn move the generators the cables and magnets, thus producing electricity. Offshore substations convert the energy produced by multiple WECs into electricity suitable for grid use (Seabased. 2022).

Next, another device is mentioned that, despite not having a TRL greater than 6, is considered relevant due to its minimum technical requirements:

- GEL (TRL 4): developed by Seapower SCRL in collaboration with Umbra Group. The system is based on a point absorber located on the surface, made up of a floating body, connected to a support structure, free to oscillate around a horizontal axis due to wave action. It contains a permanent magnet electrical generator, integrated into the actuator, which allows the transformation of the linear movement induced by the waves into a rotary movement. A 5 m device can produce a power of 60 kW from a 1.5 m high wave. The system can produce approximately 150,000 kWh per year (GEL. 2022).

Environmental impact of using wave energy: Wave energy harvesting systems must solve a series of problems before they can be widely used. In any case, it should be noted that many of them only affect devices located on the coast. Possible negative impacts include the following (Guillou *et al.* 2020, Khare *et al.* 2020):

- Visual impact: it always depends on the type of technology and its distance from the coast. In general, a submerged system, a floating buoy system, or a platform located in the deep sea, may not have a great visual impact; however, if an area is dependent on tourism, any obstruction is critical.

- Noise: the technologies produce noise, although the levels are usually lower than those of a ship; even operating at full load, they are comparable to the sounds emitted by the blowing of the wind or the breaking of the waves. These systems can be built with good sound-insulating material.

- Nuisance and destruction of marine life: could influence coastline areas and the plants and animals that live in them. Systems located on land require important modifications that affect the environment. Potential impacts include nuisance or destruction of marine biota. However, the ecology will probably recover. The effects of devices far from the coast are small. With the extraction of wave

energy, calm areas are produced in the waters, which can be used for tourist, recreational, or commercial purposes. Offshore structures provide suitable surfaces for a variety of algae and invertebrates to develop, which may colonize the devices. Therefore, from the point of view of its conservation, it is necessary to take corrective measures to avoid destruction or damage.

- Coastal erosion: most WECs concentrate energy in one area before it is captured, which can erode coastlines.

- Conflicts with navigation: once installed, they could constitute a dangerous obstacle for any vessel that cannot distinguish them or detect them by radar. This could be overcome with conventional techniques (lights, paints, reflectors, among others)

- Interference with other recreational activities: if not properly located, WECs can hinder other uses of coastal areas, such as beach enjoyment, surfing, boating, and commercial or sport fishing.

Advantages and disadvantages of wave energy: The following section presents a brief description of the advantages and disadvantages of wave energy in general, since each wave energy converter will have specific benefits or limitations depending on its structure and energy capture principles.

Advantages

- It is a renewable, sustainable, and abundant resource (Khare *et al.* 2020).

- Minimal environmental impact compared to other energies. CO₂ emissions are smaller than solar power and comparable to those associated with wind power generation (Nguyen *et al.* 2020).

- Its intensity (2-3 kW/m²) is much higher compared to other renewable sources such as solar (0.1-0.2 kW/m²) and wind (0.4-0.6 kW/m²) (Nguyen *et al.* 2020).

- WECs can capture energy up to 90 % of the time, while it is only 20 - 30 % for wind and solar devices (Xu *et al.* 2019).

- Waves can travel great distances with little energy loss. For example, storms originating on the western side of the Atlantic Ocean will transit to the western coast of Europe without significant losses (Xu *et al.* 2019).

- It varies with the seasons of the year in the same way that electricity demand does in areas with temperate climates. Likewise, it is more continuous than wind and solar (Clemente *et al.* 2021, Khare *et al.* 2020).

- It can be used in processes such as plankton extraction, marine farming, and hydrogen production

(Abdelkareem *et al.* 2018, Clemente *et al.* 2021, Khare *et al.* 2020, Prieto *et al.* 2019).

- It is predictable, as waves can be predicted in advance, unlike other resources such as wind energy (Sheng. 2019).

- The systems can cushion waves in port or erodible areas, protecting the coastline (Clemente *et al.* 2021, Khare *et al.* 2020).

- They have high flexibility for installation (on land, near the coast or offshore) (Clemente *et al.* 2021, Khare *et al.* 2020).

- Another possible use would be in ship propulsion. The relative movement of the ship about the water surface can be exploited by mechanical or pneumatic systems, placing submerged stabilizers (Clemente *et al.* 2021, Khare *et al.* 2020).

- WECs have been designed for multiple alternative purposes, such as seawater desalination (Leijon & Boström, 2018), coastal protection (Bergillos *et al.* 2020), and flood mitigation (Bergillos *et al.* 2019).

Disadvantages

- One of the main technical challenges to be investigated is the long-term survivability of WECs, especially in extreme conditions, as several devices have failed in storms (Kamranzad & Hadadpour. 2020).

- Technologies far from the coast have significant costs, due not only to maintenance and installation, but also to the mooring system, which must be checked and replaced systematically, guaranteeing that no part is lost and drifts (Khare *et al.* 2020).

- The corrosive effect of saltwater has very negative consequences on the different materials (Khare *et al.* 2020).

- The irregularity in the amplitude, phase, and direction of the wave makes it difficult for a device to obtain the maximum performance in the whole range of excitation frequencies (Khare *et al.* 2020).

- In terms of power, the resource is greater than in other renewable energies; however, the problem is that there are no natural concentrators as in other types of energy, which makes it more difficult to exploit (Khare *et al.* 2020).

- WEC performance continues to be inferior to other types of marine energy converters; In addition, it is affected by the high annual and seasonal variability of the wave resource (Guillou & Chapalain. 2018).

Wave energy costs

One of the main challenges for the exploitation of wave energy is the cost of the

technologies (Benbouzid *et al.* 2020). As with many other renewable energies, it requires high investments, due to the need to build large structures to capture a significant amount of energy.

Although the commercial viability of a wave project depends on the location of deployment and the specifics of the WEC, it is important to have a fair cost-based comparison between wave energy and other renewable sources, complementary to the technology and performance levels discussed beforehand. This also allows for a better understanding of the existing economic challenge facing this sector. The common metric is the Levelized Cost of Energy (LCoE), in €/kWh (Pecher & Kofoed. 2017). For wave potential, the LCoE is estimated at values as low as €0.33/kWh, which would be close to the commonly targeted threshold of €0.10/kWh to €0.30/kWh for renewables (Clemente *et al.* 2021).

However, these vary considerably from technology to technology and over time. For example, most estimates point to values ranging between €0.30/kWh and €1.20/kWh (Chang *et al.* 2018). These figures are essentially based on offshore wind benchmarks and institutional reports, given the lack of WEC operational benchmarks from the wave energy sector. It is also estimated that around 40% of the LCoE is attributed to operation and maintenance (O&M), 35 % to the initial investment, and 25% to replacement (Clemente *et al.* 2021).

Recent innovations have been developed that may pave the way for the economic viability of wave energy exploitation. This is, for example, the case of the Eco Wave Power project, which consists of attaching a set of small buoys, dedicated to the conversion of wave energy, to existing coastal structures such as dikes. The idea brings many benefits, it facilitates maintenance and reduces transmission lines, interactions with coastal activities, and effects on marine life. Pilot projects in Israel and Gibraltar were installed and connected to the grid (Eco Wave Power. 2022b).

Regarding combined wave and wind systems, a key challenge to solve, in addition to the different levels of maturity, is the optimization of the design of the selected technologies. Defining the number of wind turbine and WEC units, whether separate or hybridized, and their distribution, can generate significant gains in terms of costs and profitability. In the research carried out by Clark *et al.* (2019) they point out that a matrix composed of 16 wind turbines and 32 WEC units resulted in an estimated

LCoE ranging between €0.32/kWh and €0.28/kWh with a life cycle cost quite low overall. For the North Sea case study, a competitive LCoE of around €0.08/kWh to €0.09/kWh was achieved for a floating wind-wave array. Compared to a wind-only or wave-only matrix, this value is considerably lower. Implementation and operating costs were of the same order of magnitude. The foregoing corroborates the great amount of work that must be done in the field of wave energy worldwide for the use of this clean, reliable and abundant source in the coming decades.

Conclusions

Wave energy is one of the most promising ways to obtain renewable energy, being a new form of energy with enormous potential. Harvesting devices, still in a development stage, are complex, expensive, and not yet competitive with traditional generation methods; however, it is not time to repair costs but resources, as required by current demand. It is estimated that wave energy could cover 10 % of global electricity consumption. In addition, the waves have the property of being an energy accumulator, since they are capable of receiving it, transporting it from one place to another, and storing it. This characteristic can bring innumerable benefits to society, since the energy generated in any part of the ocean ends up on the continental edge, concentrating on the coasts. It is worth remembering that the main settlements of the population are in coastal areas, close to the resource. For this reason, one of the main advantages of this energy should be highlighted: its proximity to consumers. The uses of wave energy have no borders, only multiple possibilities such as the propulsion of a catamaran, the generation of electricity in an isolated community, the desalination of seawater, or the protection of erodible zones, allow us to predict technological developments that promise to be important for the energy future of nations.

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