Wave Energy: A review of technologies, performance, and costs.

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Abstract. In the last few decades, the energy demand has increased significantly. In a world where the energy majority comes from fossil fuels, the need for renewable energy sources is tremendous. Among the renewable energy sources, Wave Energy is one of the most promising, however, it is still in the initial stage of its development. This study will make a complete analysis of Wave Energy: From its creation in nature to the existing Wave Energy Converters (WECs), evaluating the different technology's performance and estimating the cost of implementation compared to other energy sources.

Keywords. Wave Energy, Wave Power, Renewable Energy, Technology, Review, Performance, Cost, Economics.

1. Introduction

In the last decades, the world population began to increase incredibly fast. It took humans hundreds of thousands of years to get to the first billion people, but it only took ten years to achieve the last. On the fifteenth of November of 2022, the world's population reached 8 billion people.

In a world that is getting "smaller" every day thanks to the help of the internet and modern technologies, it is practically unthinkable that someone can live without energy, which might explain why electric energy is one of the world's most valuable assets.

Unfortunately, most of the world's primary energy consumption (the amount of energy generated) is composed of fossil fuel energy sources (oil, coal, and natural gas). In 2010, about 80% of the global primary energy consumption came from these sources [1], and in 2022, twelve years later, the scenario hasn't changed [2]. This fact is an enormous problem because beyond having built an entire system around a finite fuel that someday will deplete, these fuels are also highly pollutive.

Emissions from coal-fired power plants are one of the largest sources of air pollution, significantly affecting both air and water quality. The most harmful to human health are particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), nitrogen oxides (NO_x), carbon dioxide (CO_2), sulfur dioxide (SO_2), methane (CH_4), volatile organic compounds (VOC_s) and over 80 hazardous air pollutants such as mercury, lead, arsenic, and benzene [3].

Besides being harmful to our health, various of them are also harmful to the environment. For example, sulfate and nitrate aerosols have a major impact on climate. They reflect incoming solar radiation, cooling the atmosphere and altering microphysical cloud properties. Sulfates can also persist in the atmosphere for a considerable time and be transported over long distances representing a regional and global problem. Greenhouse gases like CO_2, CH_4, and nitrous oxide (N_2O) are also terrible for the environment. They are kept trapped in the atmosphere and warm up the planet, with Fossil-fueled power plants being the largest anthropogenic source of their emissions [3].

That's why it is indispensable that we, as a global society, understand the gravity of these emissions and work to minimize and possibly end the use of combustion engines, withal investing in renewable energy sources to produce clean and healthy energy.

In 2022 renewable energy sources represent 13,5% of the world's primary energy consumption [2], and although it is a very small percentage they have an incredible growth potential. This occurs because various renewable energy sources don't receive the attention necessary to develop, like Wave Energy [4].

Wave Energy (WE) is a new form of renewable energy that can generate electricity through the motion of waves, and it promises to be one of the most efficient renewable energy sources. The Intergovernmental Panel on Climate Change (IPCC) puts the potential annual global production at 29,500 TWh, which is almost ten times Europe's annual electricity consumption (3,000 TWh) [5].

This paper will review Wave Energy and analyze its diverse technologies, their performance, and estimate their cost of implementation.

2. Research Methods

The methodology utilized to approach and study this topic was extant research in scientific databases like Science Direct and search mechanisms like Google.

At first, I focused on learning the basic concepts of electricity generation. Then, I proceed to study the scenario of the world's energy mix, the differences between electricity generation and primary energy consumption, how to differentiate them, and the effects that the pollutants released by fossil fuels have on the environment and human health. At last, I searched for the use and development of renewable energies and the operation and particularities of Wave Energy.

After getting well acquainted with all these concepts, I started studying and critically analyzing scientific papers that discourse about Wave Energy technology reviews, papers that analyze and compare their efficiency, and some that discuss its costs, in order to have a full view of the topic.

3. Discussion

3.1 Creation of Wave Energy

The generation of Wave Energy (WE) occurs as a consequence of diverse phenomena. Earth surface gets unevenly heated due to differences in solar irradiation which results in airflow. Part of this (airflow) energy is transferred to the seawater in the shape of waves by the wind touching the sea surface. Then, the kinetic energy develops within the waves through a phenomenon called 'wave energy' that can be harvested using WE devices/converters [4].

Unfortunately, the energy stored in waves is not uniform, and it differs due to various factors: First, the direction of waves in deep water varies with the change in the direction of the wind field. Secondly, the movement of the water particles creates a friction force in which the seabed causes the waves to lose energy during their travels toward the shore. Third, there is the timescale and the wave diffraction when approaching the shore [4].

3.2 Types of Wave Energy Converters

As there are factors that alter the energy available on the waves, there are also different technologies adapted to different situations.

Wave Energy Converters (WECs) are designed to convert the kinetic energy within waves to electricity, and there is a wide variety of technologies. There are several methods to classify WECs, according to location, working principle, and size (''point absorbers'' versus ''large'' absorbers). The classification in **Fig. 1** is formulated on the working principle of the converters, and the examples selected are projects that at least reached the prototype stage (or were an object of extensive development effort) [6].

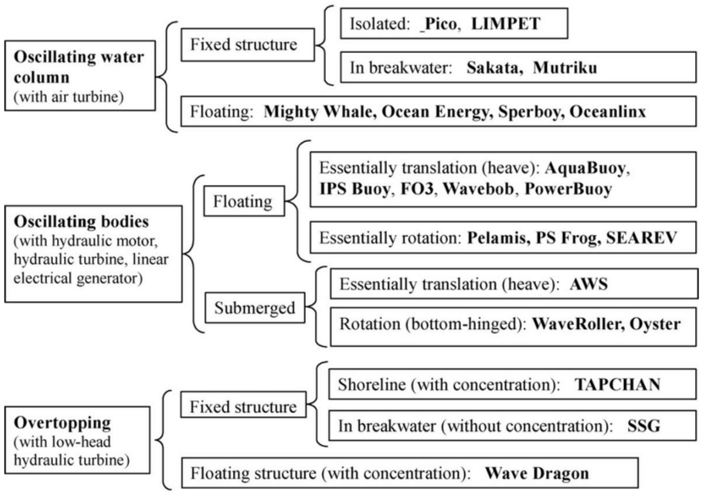

Fig. 1 – Classification of Wave Energy Converters (WECs) [6].

Location:

Regarding the location, the WECs are divided into three categories: Shoreline, Near-shore and Off-shore. The devices installed at the coastline, where the maximum depth is 15m are on the Shoreline; the ones installed at a depth fewer than 25m are named Near-shore devices; and devices placed at the sea bottom (where the sea depth is within the range of 25m-200m) are Off-shore [4].

Shoreline devices offer the advantages of being close to the utility network, being simple to maintain, and having a lower risk of being damaged in harsh weather by wave attenuation as they travel over shallow waters. On the downside, the shallow waters also reduce the wave harvesting power. This can be partially countered by utilizing this system in a natural energy-concentrated place [4].

Devices in the Near-shore are bound to the seabed, providing a stable base against an oscillation body. A downside is that shallow water causes weaker waves, like shoreline devices, reducing harvesting capability [4].

Off-shore devices are set in deep waters to seek deep ocean waves with higher energy content. Besides harvesting more energy, these devices are more difficult to build and maintain, not to mention that they must be assembled to withstand extreme circumstances, making them expensive to manufacture [4].

Working principle:

The WECs are grouped into three categories: Overtopping, Oscillating water column (OWC), and Oscillating Body Systems.

Overtopping. These devices utilize low-head hydraulic turbines and work following this principle: They face exactly the trajectory of the waves and then direct them to a catchment tank. A mechanism is responsible for concentrating the widely distributed WE to a narrow ramp, which converts horizontally directed wave flux to a vertically WE by lifting the incoming water. Then, the water fills up a reservoir whose main function is to provide a stable supply to a conventional low-hear hydraulic turbine (or set of turbines), as shown in **Fig. 2** [4].

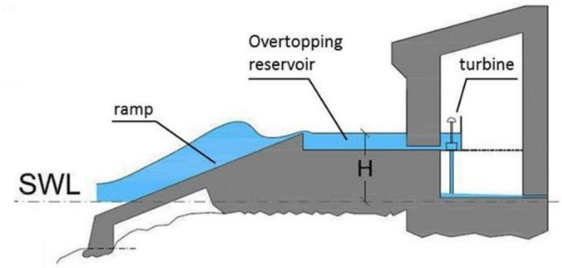

Fig. 2 – Overtopping Energy Conversion system [7].

Oscillating Water Column (OWC). It is the most common Shoreline design; it utilizes an air turbine and is composed of a partially submerged chamber with a small exit at the top and a large opening below sea level. It is designed to let the waves change the water level in the chamber, allowing it to rise and fall with the water flow. The motion of the sea level causes the air above to continuously compress and decompress generating a high-velocity stream of air that moves a turbine. Therefore, in this process, OWC treats as a pneumatic gearbox by turning slow waves to fast air flows in a suitable way to power the turbines [4]. **Fig. 3** depicts the basic principle of OWC.

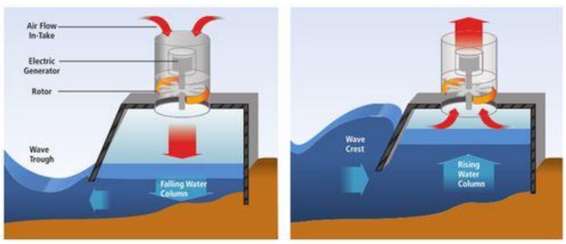

Fig. 3 – Oscillating Water Column Energy Conversion System [8].

The Oscillating Body Systems are composed of different technologies. According to the shape, size, and angle of the relative incident wave direction of the body, they can be divided into three types: Point Absorber, Attenuator, and Terminator [9].

For research purposes, I will only address a few of the available technologies. The Oscillating Wave Surge Converter (OWSC), a Terminator; and the Submerged pressure differential system, a Point Absorber.

Oscillating Wave Surge Converter (OWSC). An OWSC is composed of a hinged deflector (terminator) that travels back and forth in response to the wave's horizontal velocity. **Fig. 4** shows an example of this mechanism [4].

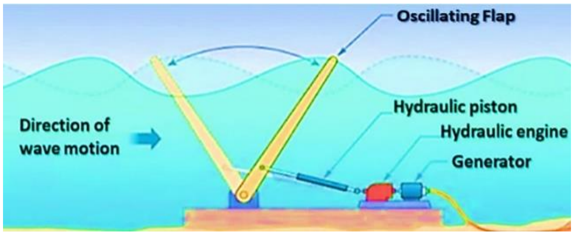

Fig. 4 – Oscillating Wave Surge Converter Energy Conversion System [10].

Submerged pressure differential. This is a submerged device that exploits the pressure difference between wave crests and troughs above it. It divides into two sections: a fixed air-filled cylindrical chamber on the seabed and a moving top cylinder. The water pressure above the device compresses the air within the cylinder when a crest passes over it, causing the upper cylinder to descend. The water pressure on the apparatus drops as a trough goes by, causing the upper cylinder to rise, as shown in **Fig. 5**. Because a portion of the device is attached to the seabed, these devices are implemented close to shore [4].

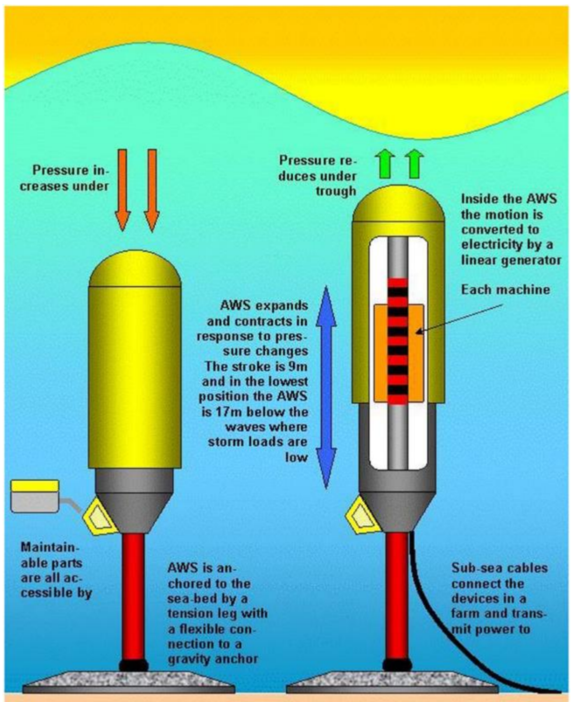

Fig. 5 – An example of a Submerged pressure differential system: The Archimedes Wave Swing [11].

3.3 Evaluation of the WECs performance

Wave power generation technology is not fully mature yet, and there are only a few successful commercial development cases. This is why it is extremely important to study and research the present capacity and future potential of Wave Energy, so we can gain the confidence of potential investors and further develop this technology [12].

Considering the needs of Wave Energy, the energy capture, economic technology cost, reliability, environmental friendliness, and adaptability were appointed as five indicators to qualify the analysis [9].

The evaluation method chosen is the AHP, which is appropriate for the multi-criteria comprehensive evaluation of WECs. First, because the available device parameters are relatively few, and second, it has the advantage of not requiring too much data to carry the optimization and ranking [9].

After applying the AHP, we can obtain a comprehensive performance evaluation of various WECs. It shows that the overall performance of the Terminator type is the best among various WECs, followed by the Point Absorber and the OWC type. These three types of WECs have been extensively studied worldwide, which may explain their results [9].

3.4 Costs of Wave Energy production

Economic viability is one of the most crucial components of an energy Source, especially when they are in the initial stage of development (as Wave Energy is). This is the moment when investors can decide whether they are going to invest and develop this technology or not [12].

The problem is that the existing models to estimate the cost of a Wave Energy project are often oversimplified, and the results are vague, which weighs on the confidence of potential investors and constitutes an impediment to the development of these technologies [12].

The main costs in a WE plant are the following: Pre-operating cost; Construction costs; Operational expenditure (OPEX); and Decommissioning costs [12].

To properly compare the cost of different energy sources, it is necessary to develop a standard by which we can compare them. One such standard is the levelised cost, the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent. There are different models to calculate the levelised cost but in this work, we will use the discounting method [12].

The results show that Wave Energy is more expensive than any non-renewable and most renewable energies — an expected result since WE is still in its infancy [12].

The implication is that, at the moment, Wave Energy is only economically viable if subsidized. However, over time it is expected that promoters will make bigger investments based upon tested technology, which would lead to reductions in costs, and consequently, this modal would operate with market prices similar to other renewable energies [12].

4. Conclusion

As stated before, the development of renewable energies and decarbonization of the world's energy mix is of absolute importance, to a series of factors. Wave Energy is a new type of renewable energy that is in the initial stage of development, but even still, it promises to be one of the most efficient energy sources. However, the success of this technology is determined by several factors, as addressed in this review. This paper analyzed the WECs in the existing literature, reviewed the technical principles of wave power generation, and briefly evaluated their costs.

By analyzing the available WECs and utilizing the AHP to evaluate its performances, the following conclusions are drawn:

(1) Based on technical principles, Wave Energy technology can be divided into three types according to the energy utilization technology principle: Oscillating Body type, Oscillating Water Column type, and Overtopping type [9].

(2) Considering the device realization, OBWEC can be subdivided into Point Absorber, Attenuator, and Terminator type according to the designed float size and angle of relative incident wave direction. OWCWEC and OWEC can be grouped into floating and fixed types according to the fixation method [9].

(3) In terms of overall performance, the Terminator type of various typical WECs is the most advantageous, followed by the Point Absorber and the OWC type [9].

In this paper, a thorough review of the economic viability of Wave Energy was also presented. The results indicate that, at the moment, an MWh generated from wave power is more expensive than conventional sources and most other renewables. Therefore, WE installations can only be economically viable if favored by subsidies [12].

There are ways of improving their income, such as improving the converters, but it will require more research, investments, and technology. It is also necessary to include indirect incomes (as an income from selling carbon emissions credit, for example) to derive appropriate conclusions on the competitiveness of Wave Energy, which were not included in this paper [12].

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