WAVE ENERGY CONVERTERS

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Contents

Summary

With a vast worldwide resource – estimated to be of the order of 2 TW – wave energy can contribute significantly to alleviating the dependency on fossil fuels and thereby decreasing its harmful environmental impact. For wave energy to become a fully-fledged renewable, however, work along two lines is necessary. First, the resource must be assessed in detail. Second, efficient and reliable wave energy converters (WECs) must be developed. After briefly presenting the fundamentals of the wave resource, this chapter examines wave energy conversion technologies from different angles, beginning with a historical perspective.

Although the exploitation of wave energy is an old idea (dating back at least to the 18th century), modern research took off with the first oil crisis (1973). Today there are many different technologies, and new ones continue to appear. Four classification criteria are proposed to systematize this variety, based on the installation site, the principle of operation, the energy capture system or the position of the latter relative to waves. This is followed by a review of the most important or representative devices. The chapter is closed with a national perspective in which the major countries currently investing in the development of wave energy are represented.

1. Introduction

The dependency on fossil fuels for energy production has brought about a number of adverse effects such as: (i) excessive emission of greenhouse gases that contribute to accelerate climate change, (ii) reduced reserves (and impending exhaustion) of fossil fuels, and (iii) geopolitical issues related to the control of the reserves, which have been at the core of a number of armed conflicts over the last decades. Moreover, the continuous fluctuations of the price of oil have a negative impact on the global economy. On these grounds the governments of the most environmentally conscious nations have adopted measures to reduce the dependency on carbon fuels. Among these measures is an important investment effort to develop low carbon technologies, and in particular renewable energies such as wave energy.

There are different kinds of waves in the ocean: (1) wind waves, (2) seismic disturbance waves or tsunamis, and (3) tidal waves. Generally (and hereinafter) the term “wave energy” refers to the energy associated to wind waves. The differential heating of the Earth’s atmosphere by the Sun gives rise to winds, which in turn generate waves in a complex energy transfer. In this process of transformation of solar energy into wind and, later, wave energy, power density increases in a concentration process. The power density provided by the Sun is approximately 0.170 kWm^{-2}. The wind power density at a location 15º north or south of the Equator is on average of the order of 0.580 kWm^{-2}. The average wind wave generated by such winds has a power density of 8.42 kWm^{-2}. Thus, wind waves can be regarded as a concentrated form of solar energy.

The energy potential of wind waves has long been recognized. The first attempts to tap into this resource go back to the end of the 18th century. However, intensive research and development of wave energy conversion would only start in 1973 with the first oil crisis. A historical perspective is presented below (Section 3).

For wave energy to become a fully-fledged renewable, work along two lines is necessary: (i) the resource – which presents significant spatial and temporal variability – must be assessed and, in particular, the areas of greatest interest must be determined and their potential quantified; (ii) reliable and efficient Wave Energy Converters (WECs) must be developed. Today intensive research into wave energy conversion is being carried out in many countries. Of the existing technologies, no one can be deemed mature at this point – there is room for improvement in crucial aspects ranging from energy performance to maintenance to survivability under storm conditions.

In addition to the existing technologies, new patents continue to appear. The outlook is optimistic not least because of the interest shown by the stakeholders, private and public alike, in actively promoting research and development. This interest is driven in part by the recognition that the worldwide wave resource is vast; indeed, it is more than sufficient to set wave energy on a par with other renewables such as hydropower or wind energy. Given the good outlook for the development of wave energy, it is essential to carefully consider its environmental impact and to ensure that its exploitation is compatible with the preservation of marine life – an aspect within wave energy research that is now beginning to gain momentum.

2. The Resource

As indicated, the energy transferred from the wind to the sea surface generates wind waves. This process occurs mostly in the high seas, far from the coastlines. The resulting waves travel over hundreds of miles of open ocean with small energy dissipation until, eventually, land appears in front of them – a continent or, perhaps, an island. As waves come closer to the shoreline the water depth over which they travel decreases – waves leave deep water and continue to propagate through intermediate and, later, shallow water. This essentially means that waves, which in deep water propagate without any interaction with the sea bed, start to interact ("to feel") the bottom. The interaction manifests itself essentially in two processes – refraction and shoaling – that modify wave properties. As waves reach the shoreline, their energy is in part dissipated through breaking, in part reflected back to the sea. Moreover, in certain areas, such as bays protected by a headland, wave diffraction can occur. As a result of these physical phenomena – wave refraction, shoaling, diffraction, breaking, reflection – that occur near, or at, the coast, the nearshore wave patterns are generally much more complex than their offshore counterparts. This is especially the case where the bathymetry (the bottom contours) is irregular. Wave energy is concentrated in certain areas (the nearshore hotspots) which can be quite small, sometimes only of the order of hundreds of meters. Moving away from these areas, the resource quickly decreases.

In addition to the spatial variability of the wave resource it is necessary to consider its temporal variability, which is apparent at different time scales. At the shortest, one wave can be quite different from the following, only some seconds later; at a much longer time scale, the wave climate in January and August, for instance, will generally be very different.

Since wave energy varies depending on the zone and season, a basic requirement for the exploitation of the wave resource is its accurate assessment. Prior to the assessment of the wave resource, the wave climate has long been investigated with other ends in sight, such as sailing, port and coastal engineering, offshore engineering and naval architecture – incidentally, fields in which wave energy is mostly a nuisance. The results of these previous investigations, though useful, are often not sufficient for wave energy exploitation, so an ad hoc assessment of the wave resource is often indispensable.

Large-scale wave energy assessments have recently been, or are currently being, carried out in most developed countries with a significant resource – which, naturally enough, tend to coincide with those where wave energy conversion technologies were first developed. Much work remains to refine the scale of the analysis in the nearshore areas so that the effects of the processes described above – refraction, shoaling, diffraction, breaking, reflection – are fully accounted for, the nearshore hotspots are delineated and their resource and its variability determined.

The energy flux, or power, of a wave is expressed in terms of power per unit length along its crest. The areas of greatest interest as prospective wave energy sites present average power values between 20 and 70 $\mathrm{kWm^{-1}}$, and occur generally in the mean and high latitudes for reasons related to the distribution of winds. Specific information on these areas can be found in the bibliography. Overall, the seasonal variability of the wave resource is lower in the Southern Hemisphere, which makes many areas of South America, Africa and Australia particularly attractive for wave energy exploitation.

3. Historical Perspective

The idea of converting wave energy into other forms of energy is not new. One of the first references to the exploitation of the wave resource comes from France's Girard brothers, in 1799. There is little information on the device in question, but in the late 18th century attempts were made to use it to capture wave energy to lift sea water and later use the energy stored. Vague information exists indicating that this device was used in some areas of England. During the first decades of the 19th century the engineer M. Fursenot put in operation, in Algeria, the first device that captured wave oscillation and transformed it into energy using a system of cams and gears. WECs featuring buoyant systems that oscillate up and down on the sea's surface were – and still are – the most common systems.

A noteworthy example would be the mechanism invented by P. Wright and patented in March of 1898 under the name "Wave Motor." In 1899, 100 km south of New York a new idea in converter devices was conceived with the Ocean Grove apparatus. This was based on an intake plate which, united to the shafts of a series of pumps, raised water to a group of elevated tanks, designed to make it possible to subsequently use the potential energy of the stored water. At the Oceanographic Museum of Monaco a device functioned for ten years pumping sea water to the aquarium using wave energy. This apparatus was ultimately destroyed by the force of the waves.

The "compliant flap" was a system contrived by the French scientist Montgolfier, and developed for the first time in a pilot plant installed in the Black Sea in 1917 and later dismantled. Its rated capacity was 10 kW. It was based on a wave converter designed to use the dynamic pressures exerted by the movement of particles. The functioning of the converter was very simple, a flexible sheet was placed perpendicular to the direction of wave propagation, thereby absorbing (part of) the wave energy. At a certain depth there is barely any particle movement, so the upper part of the sheet flexed depending upon the movement of the waves. This upper part was connected to a piston which, in turn, propelled a fluid, which allowed for the exploitation of the wave energy.

But it was not until the energy crisis of 1973 when major efforts began to find a trustworthy and profitable way to convert wave power into energy. There were many ideas for WEC devices, with a large number being patented, but very few converters progressed to the testing stages, and just a very few ever managed to actually produce energy. These were the first-generation converters which laid the foundations for today's technologies. In this regard it is worth pointing out that it was in the 70s when studies aimed at a better understanding of wave mechanics were undertaken.

In the same decade in-depth research was carried out on cavity resonance devices. Most of the contemporary efforts in the use of this branch of technology were undertaken by Iosho Masuda with the Japan Marine Science and Technology Center, and by R.M. Ricafranca with the RMR Research and Engineering Services in the Philippines. The two of them, working separately, were responsible for the first commercial wave energy converters. These converters would later be called OWCs, or Oscillating Wave Columns. Their operating principle is based on exploiting the oscillation of a water column inside a chamber connected with the outer (ocean) water through an opening below the surface. The water column oscillation acts like a piston for the air in the upper part of the chamber, alternately compressing and decompressing it. The upper part of the camber is connected with the exterior through a conduit in which a turbine is installed. When the water column rises, the air is compressed and expelled from the chamber, thereby driving the turbine. When the water column falls, the air pressure in the chamber decreases and air is absorbed from outside, also driving the turbine. The turbine is connected to an electrical generator.

A British project carried out by the National Engineering Laboratory, based in Glasgow, capitalized on the knowledge acquired in the preceding years to perfect Masuda's device. This work did not progress out of the prototype phase. However, Masuda was able to put a device (called the *Kaimai*) into operation. This was a system mounted on a barge with apertures on the bottom of it. Installed along the coast of Japan it was capable of producing 1.3 MW.

Between 1976 and 1981 thirteen million pounds sterling in the U.K. were allocated by the British government for development and research in the field of marine energies. The engineer Stephen Salter of the University of Edinburgh presented a device named the "Salter Duck" after its shape when floating. Waves made the device spin as the result of a rocking movement, which was used to pump a hydraulic fluid or to compress air. It was this hydraulic fluid that drove a generator in order to produce electricity. Developed in the 80s, the project stalled when calculations indicated that its operating costs would be very high. A recent reexamination of the device produced cost figures ten times lower than those initially estimated.

Also in the U.K. (in Southampton) Christopher Cockerell worked on the design and development of a wave converter system based on the relative movement of plates connected by hinged joints. The wave produces a relative movement between each one of the plates, activating a system which pumps a high-pressure hydraulic fluid, which is then turbined for the generation of electricity. There were experiments with plates of different lengths in order to see what configuration was the most efficient, but these tests were carried out based on bidimensional waves; when the prototypes were subjected to real operating conditions they proved to be quite inefficient. In 1974 the company Wave Power Limited was founded in order to commercialize the work and patents held by Cockerell's research group. The first of these devices was huge, measuring 50 meters wide and 100 meters long.

In Oxford Robert Russell, Director of the Hydraulics Research Station at Wallingford, designed a device that would operate in shallow waters. The system, called the HRS Rectifier, was an anchored structure that breached through the surface of the water, with sluice gates closing off two tanks. One pair of sluice gates opens when the crest of the wave hits the structure. The water reaches a higher level and is diverted through a turbine towards a twin tank located at wave trough sea level. When the crest passes, the sluice gates of the second tank (which collects the turbined water) open, completing the cycle.

These WECs either did not pass the experimental phase or did not produce significant quantities of energy. But, as we said at the start of this section, they did form the knowledge base upon which many of today's devices are built.

More recently, in 1991 Queen's University of Belfast designed and tested a small device of 75 kW of power aimed at gathering information and experience in the field of terrestrial OWCs. As a result of this research, in 2000 the LIMPET (Land Installed Marine Pneumatic Energy Transmitter) was put into operation on the Scottish island of Islay, with a power of 500 kW and capable of providing electricity to 400 homes.

4. WEC Classification

Over the last decades, and based on a greater knowledge of wave mechanics, many WECs have appeared. WECs can be classified according to the following criteria.

4.1. Classification According to the Installation Site

According to this criterion three types of WECs can be distinguished: (i) onshore WECs, i.e. WECs whose systems are located entirely onshore; (ii) onshore-nearshore WECs, i.e. those that capture wave energy in the nearshore and convert it into electricity in an onshore facility; and (iii) nearshore-offshore WECs, i.e. those that are deployed either nearshore or offshore – in any case, without an onshore installation. The latter group, the most numerous by far, may be subdivided according to whether the WECs are floating or resting on the seabed. Whereas WECs founded on the seabed are generally intended for nearshore deployment, floating WECs may be installed either nearshore or offshore.

4.2. Classification According to the Principle of Operation

There are three categories within this classification: (i) overtopping devices, or WECs whose principle of operation is based on waves overtopping a barrier and their water being collected at a reservoir above the mean sea level; (ii) wave-activated bodies, or devices that capture wave energy through bodies that are made to oscillate at the passage of each wave; (iii) Oscillating Water Columns (OWCs), which convey the wave energy to a second fluid (air) which in turn drives a turbine-generator group.

4.3. Classification According to the Energy Capture System

This criterion leads to two categories. The first is composed of devices that generate electricity by means of turbines coupled to a generator; this category, which is the most numerous by far, can be further divided according to the fluid driving the turbine – water, oil or air. The second group consists of devices that use wave energy to move a mechanism (whether linear or rotational) and then transform this motion into electricity without an intermediate fluid.

4.4. Classification According to the Position of the Capture System Relative to the Wave Direction

This criterion distinguishes between two types of WECs: point absorbers and line absorbers. In the point absorbers the capture system does not have a predominant dimension – it can be represented on a nautical chart as a point – and moves perpendicularly to the sea surface. A typical example is a buoy. In the line absorbers the capture system has a predominant dimension (length), which can be transverse or longitudinal to the incoming wave direction.

5. A Review of WECs

Having discussed several criteria on which WECs can be classified, this section presents a number of converters chosen for their level of development or otherwise interest. The aim is not to carry out an exhaustive study of each device but rather to review the state of the art, focusing on the most noteworthy WECs within the large variety of existing designs. To systematize the review, the first criterion of classification (installation site) is adopted.

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Biography Sketches

Gregorio Iglesias was born in 1969; he received his degree in Civil Engineering from the École Nationale des Ponts et Chaussées (Paris) in 1992 and his Ph.D. from the Polytechnical University of Madrid. From 1993 to 2004 he worked at the University of A Coruña (Spain), first as Assistant Professor, then as Associate Professor in Hydraulic Engineering. Since 2004 he works at the University of Santiago de Compostela as Associate Professor in Hydraulic Engineering, and since 2010 as Coordinator of the Research Group on Water and Coastal Engineering of the same University. His research focuses on coastal hydrodynamics, with emphasis on the assessment of marine energy resources (wave and tidal stream energy) using numerical modeling and field data, and on the development of wave energy converters by means of physical model tests and numerical models, with a particular interest on overtopping and OWC converters. He is one of the inventors of the WaveCat, a floating WEC patented by the University of Santiago de Compostela. Regarding the resource assessment, he is the principal investigator of the currently ongoing, nation-wide project “Assessment of Renewable Marine Resources”, financed by Spain’s Ministry of Science and Innovation. He has also served as principal investigator in a number of projects that started wave energy research in N Spain.

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