Ocean wave energy extraction: Up-to-date technologies review and evaluation

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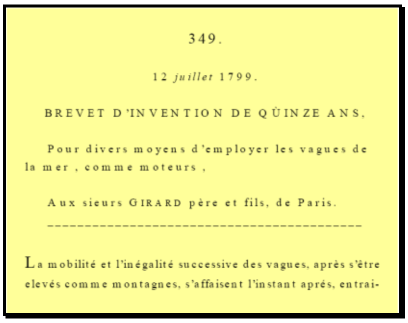
Abstract—**The potential of electric power generation from marine renewable energy is enormous. Ocean waves are being recognized as a resource to be exploited for the sustainable generation of electrical power. The high load factors resulting from the fluid properties and the predictable resource characteristics make ocean waves particularly attractive for power generation and advantageous when compared to other renewable energies. Regarding this emerging and promising area of research, this paper presents a complete review of wave energy technologies describing, analyzing and fixing many of the concepts behind wave energy conversion. The proposed review will specifically highlights the main wave energy conversion projects around the world at different levels (demonstration stage, in production, and commercialized projects). In addition, a discussion will highlight challenges that wave energy converters need to overcome to become commercially competitive in the global energy market.**

Keywords—**Marine renewable energy, wave energy converter (WEC), design, challenges.**

I. Introduction

One of the very attractive renewable energy sources is the ocean. Indeed, it covers around three quarters of the earth surface and energy can be extracted from the waves, tides, currents, temperature gradients, and salinity gradients. Wave energy, in particular, is spatially more concentrated than both wind and solar energy; it is also more persistent and predictable than wind energy. The global wave power resource has been estimated to be at least 1 TW, with a potential annual energy production of about 2000 TWh; this is comparable to the energy production from nuclear or hydropower [1-2].

The history of wave power research spans over more than two hundred years. The Frenchman Pierre-Simon Girard is recognized as the first holder of a wave power patent in 1799 [3] (Fig. 1a). Yoshio Masuda may be regarded as the father of modern WEC technology, with studies in Japan since the 1940s. He developed a navigation buoy powered by wave energy, equipped with an air turbine, which was in fact what was later named as a (floating) oscillating water column (Fig. 1b). These buoys were commercialized in Japan since 1965 (and later in USA) [4]. Since then many different other concepts have been conceived. Some of these have come no further than the drawing table, others have made it into small scale models, and a few have also moved on to ocean testing.


349.

12 *juillet* 1799.

BREVET D'INVENTION DE QUINZE ANS,

Pour divers moyens d'employer les vagues de la mer, comme moteurs,

Aux sieurs GIRARD père et fils, de Paris.

La mobilité et l'inégalité successive des vagues, après s'être elevés comme montagnes, s'affaisent l'instant aprés, entrai-

(a) Pierre-Simon Girard WEC patent.

(b) Yoshio Masuda oscillating water column.

Fig. 1. WEC history review.

The technology is still immature and would not commercially exist if it was not subsidized by governments. Therefore, to become a competitive market, it is crucial for the industry to reduce the overall cost of electricity generated from waves. There are many different WEC technologies, and it is not clear which one is superior. WECs developers tend to focus on the prime-mover aspect and use off-the-shelf electrical systems to generate electrical power. These electrical systems usually include a gearbox or a hydraulic system to interface a slow moving prime mover to a conventional high-speed rotary machine. The use of gearboxes or hydraulics introduces potential extra-scheduled and unscheduled maintenance costs. Moreover, the maintenance for offshore devices is much more expensive than onshore equivalents and limited by weather conditions, which results in increased down-time costs.

The present review aims at giving an update of the most recent trends regarding main wave energy conversion projects around the around at different levels (demonstration stage, in production, and commercialized projects) with respect to overviews already published in the past years [4-7]. In addition, a discussion will highlight challenges that wave energy converters need to overcome to become commercially competitive in the global energy market.

II. Wave Energy Background

Figure 2 show an atlas of the global power density distribution of the oceans. The north and south temperature zones have the best sites for capturing wave power. The prevailing winds in these zones blow strongest in winter. Increased wave activity is found between the latitudes of 30° and 60° on both hemispheres, induced by the prevailing western winds blowing in these regions.

A wave resource is typically described in terms of power per meter of wave front (wave crest length) [5].

$$P_{w\_f} = \frac{1}{8\pi}\rho g^2 A^2 T \quad (1)$$

where ρ is the water density (approximately 1000 kg/m^3), g is the gravity acceleration, A is the wave amplitude, and T the wave period. It can also be described in terms of wave power per meter crest length (P_{w_mcl}).

$$P_{w\_mcl} = \frac{1}{32\pi}\rho g^2 H^2 T \quad (2)$$

It should be noted that the wave height H is defined as equal to $2A$ (Fig. 3).

III. Wave Energy Converters

A. WEC Concepts

WECs have been developed to extract energy from shoreline out to the deeper waters offshore. These devices are generally categorized by the installation location and the Power Take-Off (PTO) system. Locations are *shoreline*, *near shore* and *offshore* (Fig. 4). In this context, most devices can be characterized as belonging to six types: Attenuator; Point absorber; Oscillating wave surge converter; Oscillating water column; Overtopping device; Submerged pressure differential (Fig. 5).

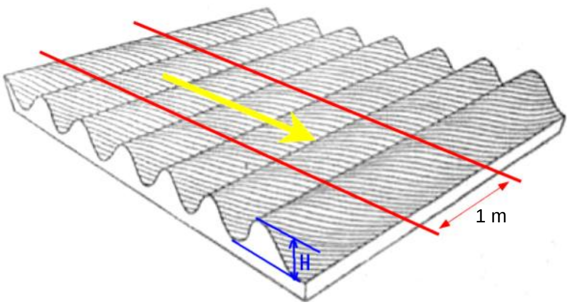


Fig. 3. Wave dimensions.

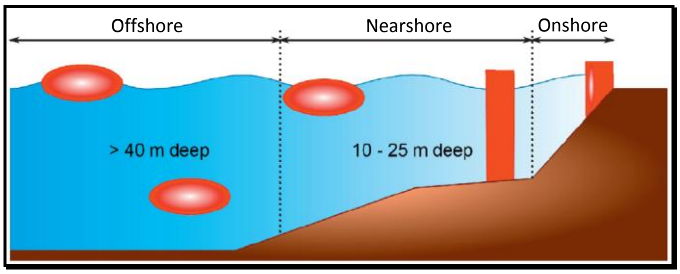


Fig. 4. WECs location.

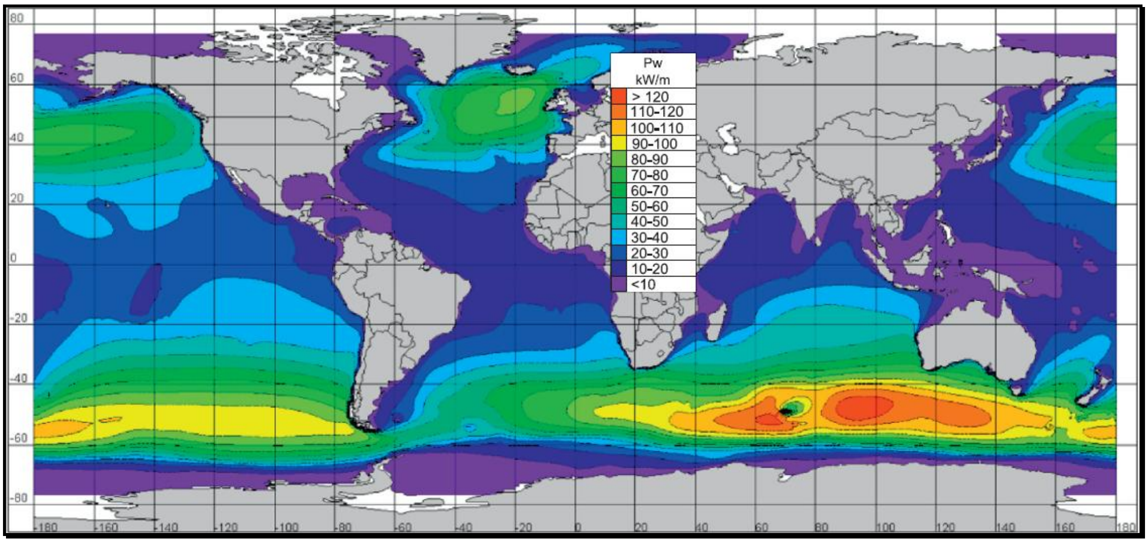


Fig. 2. Global annual mean wave power estimation in kW/m spanning 10 years period [6].

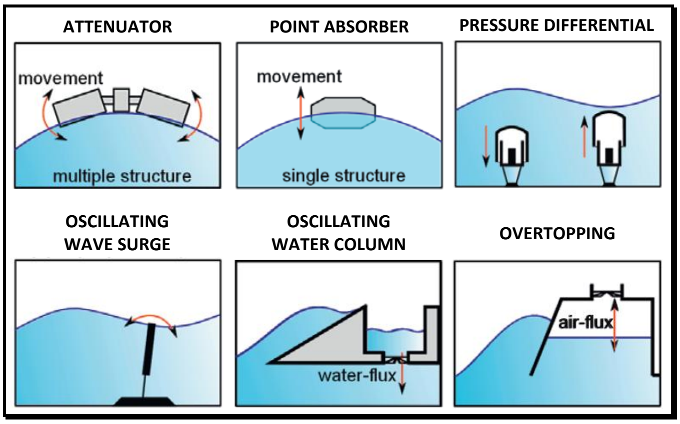


Fig. 5. WECs concepts.

B. WEC Main Projects

Figure 6 summarizes the main WEC projects in terms of concepts and locations. It should be mentioned that this figure tries to summarize the main and well-known WEC mainly over the demonstration stage. Indeed, there is a large number and variety of WEC that vary in concept and design. In addition to the fact, that there were more than 1000 patents in 2009 [6]. In fact, all of these projects should be considered as in early stages if compared to other renewable technologies (i.e. wind).

IV. Wave Energy Extraction

Figure 7 summarizes the different conversion stages. In particular this figure shows that there is a variety of ways to extract power from waves: pneumatically, hydraulically, and mechanically (PTO) [8]. This mechanical interface is used to convert the slow rotational speed or reciprocating motion into high speed rotational motion for connection to a conventional rotary electrical generator. In this context, attention will be directed at the mechanism needed to convert wave energy into electricity as most building blocks in the generation system remain nearly the same after being transformed into the electrical form [9].

Linear generators are an option on the testing stage, but they are not yet currently used in most developed WECs [10-14]. In particular, different types of linear generators were investigated for the AWS WECs [15-16]. These investigations have led to the conclusion that the transverse flux permanent magnet generator is a good candidate in terms of higher power density and efficiency. The use of permanent magnet synchronous generator is an intermediate option [17-19]. The use of induction generators implies a specific mechanical PTO that induces additional losses affecting the WEC overall efficiency [20-23]. In this context, there are still mechanical engineering challenges. Table 1 summarizes the PTO systems and the electrical generator options for the some of Fig. 6 WEC projects [5].

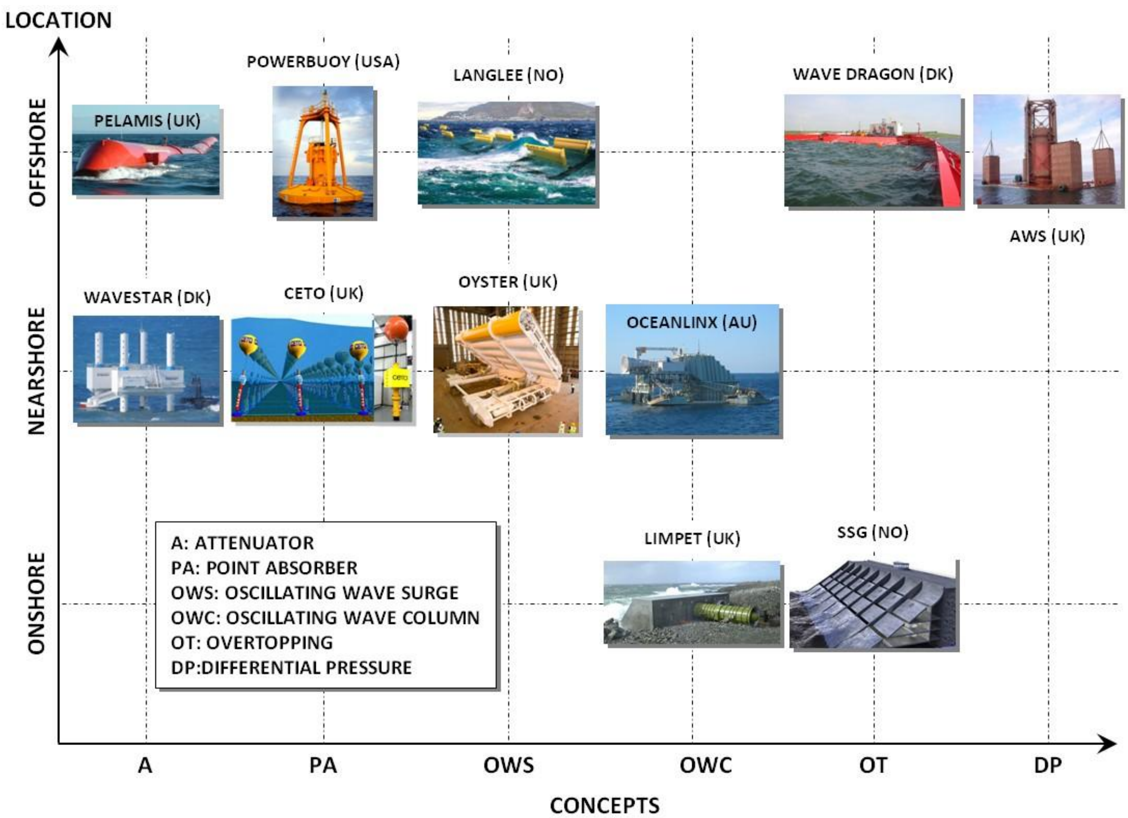


Fig. 6. WECs main projects.

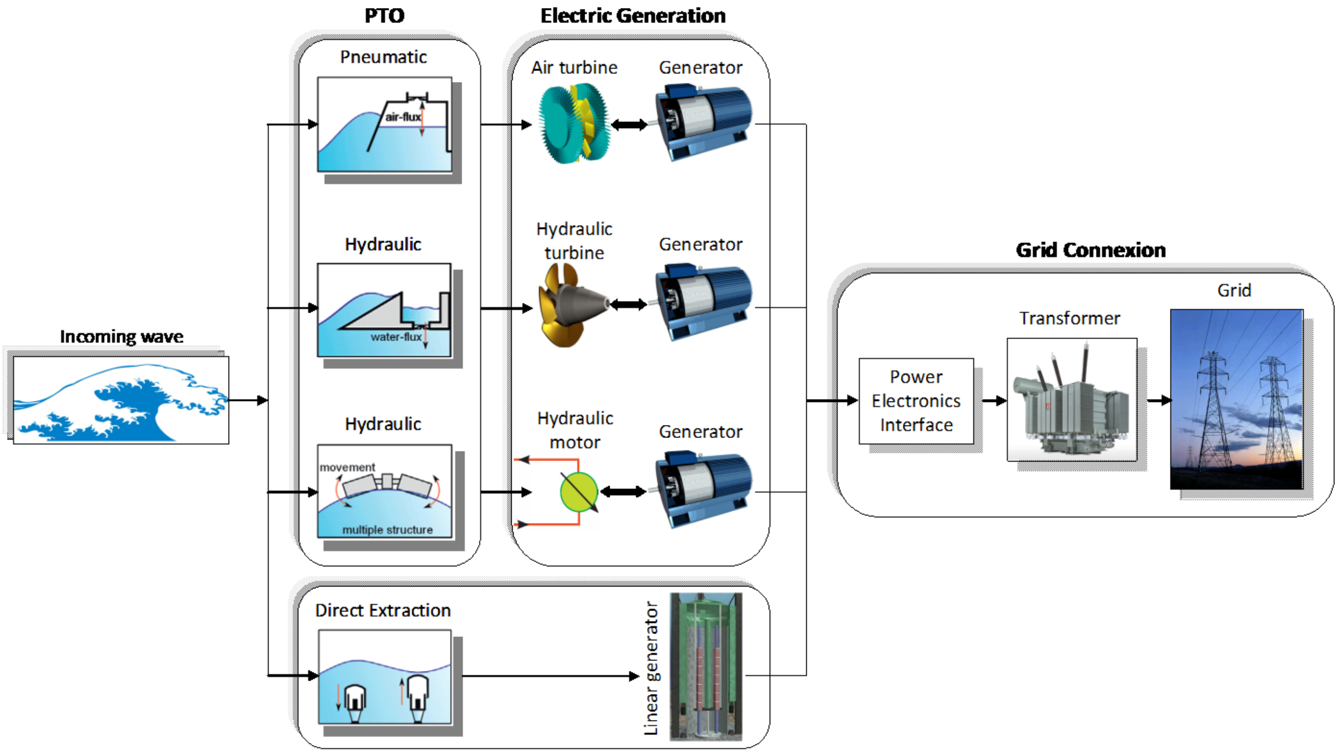


Fig. 7. WEC different type of conversions.

TABLE 1. WEC MAIN PROJECTS PTOS AND GENERATORS.

WEC	PTO	Generator
PELAMIS	Attenuator/Hydraulics	Cage induction generator
POWERBUOY	Point absorber	Permanent magnet synchronous generator
OYSTER	Oscillating wave surge converter	Cage induction generator
LIMPET	Oscillating water column & Wells turbine	Cage induction generator
OCEANLINX	Oscillating water colum & Denniss-Auld turbine	Cage induction generator
PICO [5]	Oscillating water colum & Wells turbine	Doubly-fed induction generator
WAVE DRAGON	Overtopping & Kaplan turbine	Permanent magnet synchronous generator
AWS	Direct drive	Linear permanent magnet generator

V. WAVE ENERGY CONVERTER MOORING

To use wave energy for electricity generation, WECs must be anchored to the seabed and moored by cables. Similar to other offshore structures moored on the sea floor, a typical WEC mooring system is likely to be composed of three parts: the mooring line, the connectors and the anchor. Chain, wire rope and synthetic fiber rope are the three main mooring line types that are used in offshore structures and could be used for WECs [24]. There are many kinds of connectors used on WECs and other marine structures [24-25]. Anchors are the terminals that transfer the whole system forces to the seabed. The main mooring types, which may be suitable for WECs, can be classed into two kinds as spread mooring and single point mooring. There are several sub-types and it is difficult to define which one is the best without considering the WEC type, location, safety, and cost [26-27].

Mooring design is a critical part of a WEC project. The devices are generally thought to be used in areas of demanding environmental loads due to waves, current and wind. These survivability issues are addressed in existing offshore standards, such as the DNV-OSE301 [28]. In addition, the mooring arrangement can have a direct influence on the WEC operation and on the economic viability of the project [29]. It seems that catenary in spread mooring, catenary anchor leg mooring (CALM) and single anchor leg mooring (SALM) in single point mooring are more popular in practical projects [30].

VI. CHALLENGES FOR COMMERCIAL VIABILITY

It has been proven that wave energy extraction is very attractive as it is spatially more concentrated than both wind and solar energy; it is also more persistent and predictable than wind energy. On the other hand, the development, from concept to commercial stage, has been found to be a very slow and expensive process [31]. Indeed, it is difficult to follow what was done in the wind turbine industry where at first, small machines where developed first, and were subsequently scaled-up to larger sizes and powers for massive deployment. In fact, optimal wave energy absorption involves some kind of resonance. This implies that WECs geometry and size are linked to wavelength. So, if pilot plants are to be tested in the open ocean, they must be large structures [4].

In this specific context, challenges that WECs should to overcome to become commercially competitive leading to massive deployment could be summarized as:

– As for offshore converters, WECs should withstand extreme wave condition leading to difficult and costly maintenance operations.
– As above discussed, mooring design is a critical part. In addition to the demanding environmental loads due to waves, current and wind, the mooring system should also withstand constraints due to the WEC alignment for capture optimization.
– Higher costs of construction, deployment, and maintenance need to be supported with substantial financial support from governments.

VII. Conclusion

As wave energy is having more and more interest and support as a promising renewable resource, although it is still immature compared to other renewable technologies. This paper has proposed an up-to-date review of wave energy technologies with respect to overviews already published in the past years. A discussion has concluded the paper highlighting the challenges that wave energy converters should to overcome to become commercially competitive leading to massive deployment.

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