An Up-to-Date Technologies Review and Evaluation of Wave Energy Converters

Hosna Titah-Benbouzid, Mohamed Benbouzid

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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 particular, mooring will be discussed, as it is a key feature behind massive deployment of wave energy converters. Finally, 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, design, challenges.*

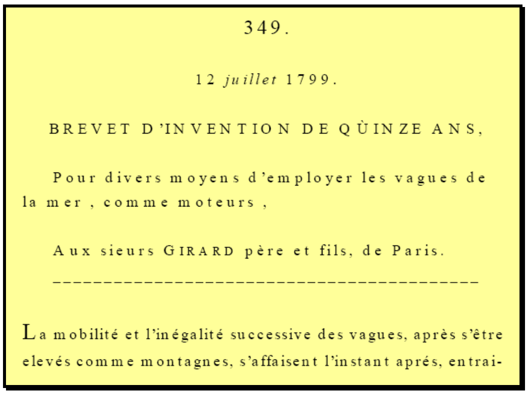
Nomenclature

WEC = Wave Energy Converter;
PTO = Power Take-Off;
P_{w_f} = Power per meter of wave front;
P_{w_mcl} = Power per meter crest length;
ρ = Water density (approximately 1000 kg/m^3);
g = Gravity acceleration;
A = Wave amplitude;
T = Wave period.

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 [1-4].

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 [5] (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).


349.

12 *juillet* 1799.

BREVET D'INVENTION DE QÙINZE 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.

These buoys were commercialized in Japan since 1965 (and later in USA) [6]. 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. The technology is still immature and would not commercially exist if governments did not subsidize it. 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 downtime 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 [6-13]. In particular, mooring will be discussed, as it is a key feature behind massive deployment of wave energy converters. Finally, 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) [8].

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

It can also be described in terms of wave power per meter crest length (P_{w_mcl}).

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

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

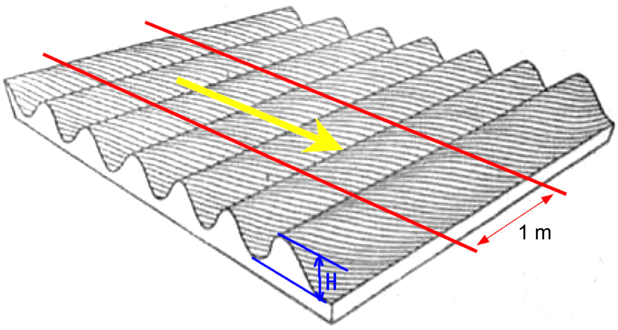


Fig. 3. Wave dimensions.

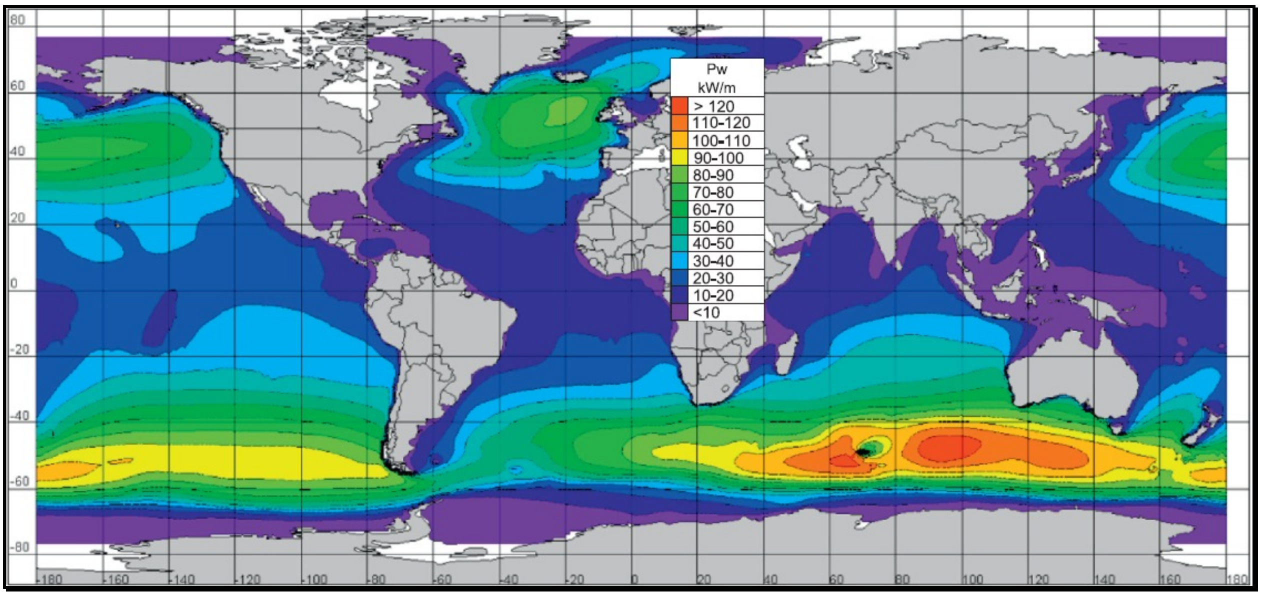


Fig. 2. Global annual mean wave power estimation in kW/m spanning 10 years period [10]

III. Wave Energy Converters

III.1. 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).

III.2. 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 [10]. In fact, all of these projects should be considered as in early stages if compared to other renewable technologies (i.e. wind).

In this particular huge developing context, it should be noted a new French WEC project called *EM Bilboquet* [14-15]. The PTO extracts the mechanical power due to incoming waves by a system made up of a cylindrical buoy sliding along a partially submerged structure (Fig. 7). This structure is made up of a vertical cylinder, referenced in the following as spar, with a damping plate attached at its keel. Energy resulting from the relative motion between the two concentric bodies is harnessed by rack-and-pinion, which drives a permanent magnet synchronous generator through a gearbox [16].

IV. Wave Energy Extraction

Figure 8 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) [17]. 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 [18].

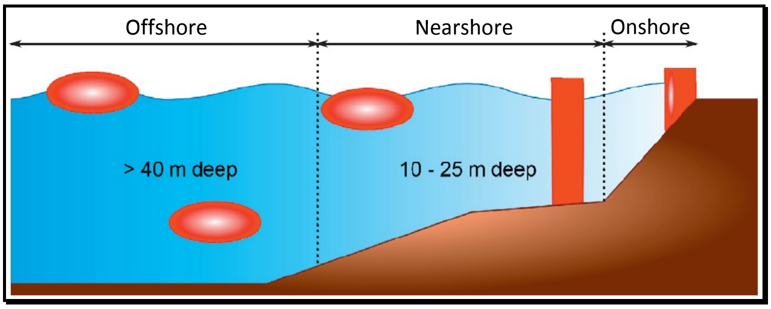


Fig. 4. WECs locations.

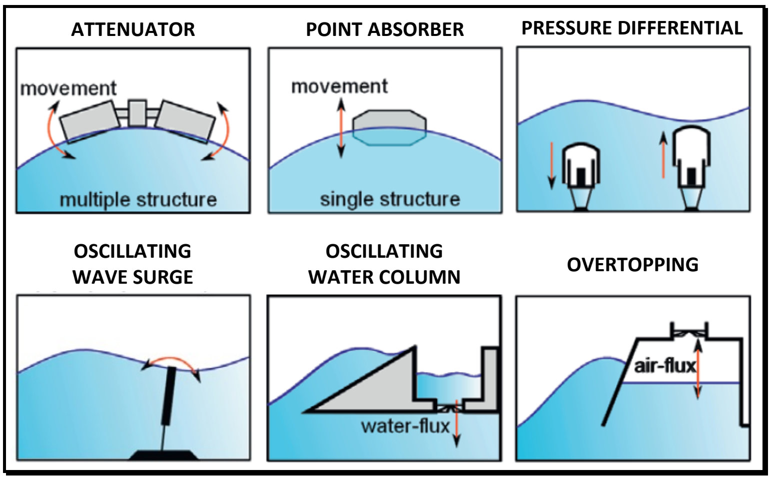


Fig. 5. WECs concepts.

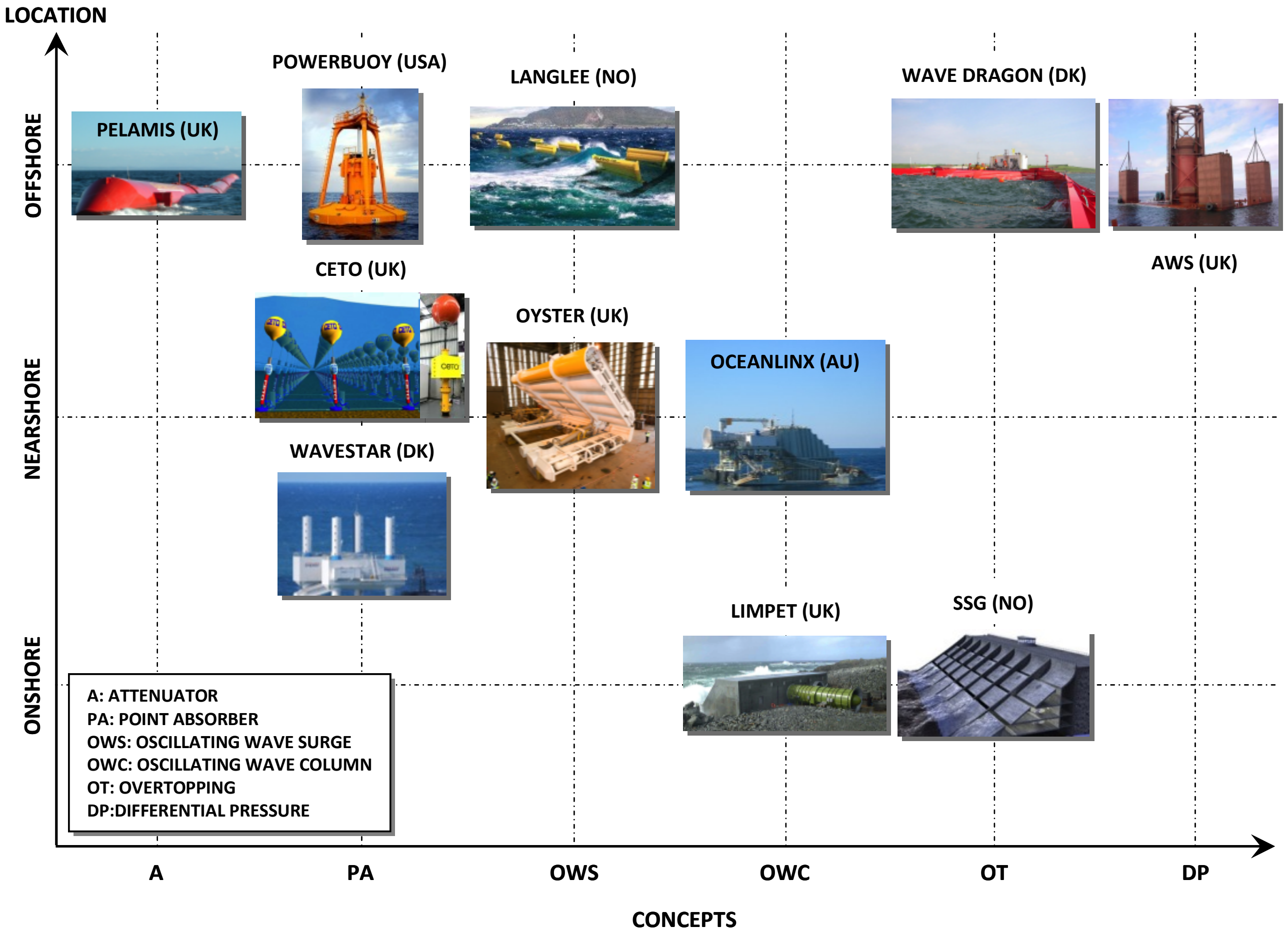


Fig. 6. WECs main projects.

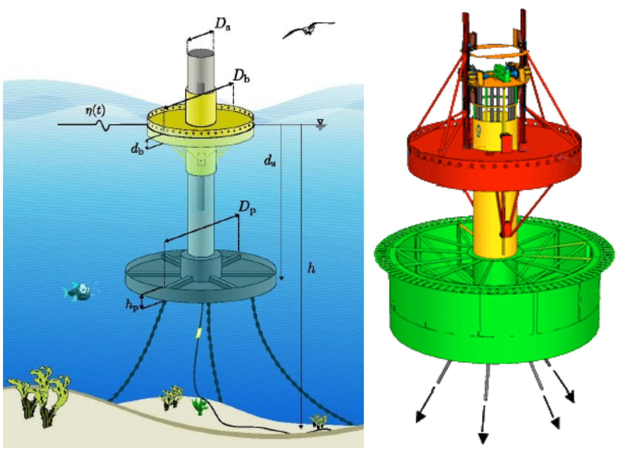


Fig. 7. The *EM Bilboquet* French wave energy converter.

Linear generators are an option on the testing stage, but they are not yet currently used in most developed WECs [19-24]. In particular, different types of linear generators were investigated for the AWS WECs [25-27]. 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 [16], [28]. The use of induction generators implies a specific mechanical PTO that induces additional losses affecting the WEC overall efficiency [29-32]. In this context, there are still mechanical engineering challenges in terms of electrical generator offshore suitability [10], [33]. Table 1 summarizes the PTO systems and the electrical generator options for the some of Fig. 6 WEC projects.

V. Wave Energy Converter Mooring

To use wave energy for electricity generation, WECs must be anchored to the seabed and moored by cables (Fig. 9). 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 [38-40]. Chains provide good catenary stiffness and are abrasion resistant. However, their restraining stiffness may not be appropriate for some WECs. They can hamper the oscillation motion required to convert energy. Synthetic ropes are advantageous because of their buoyancy property, which will reduce mooring weight influence during normal operation and are good candidates for deep-water applications [41].

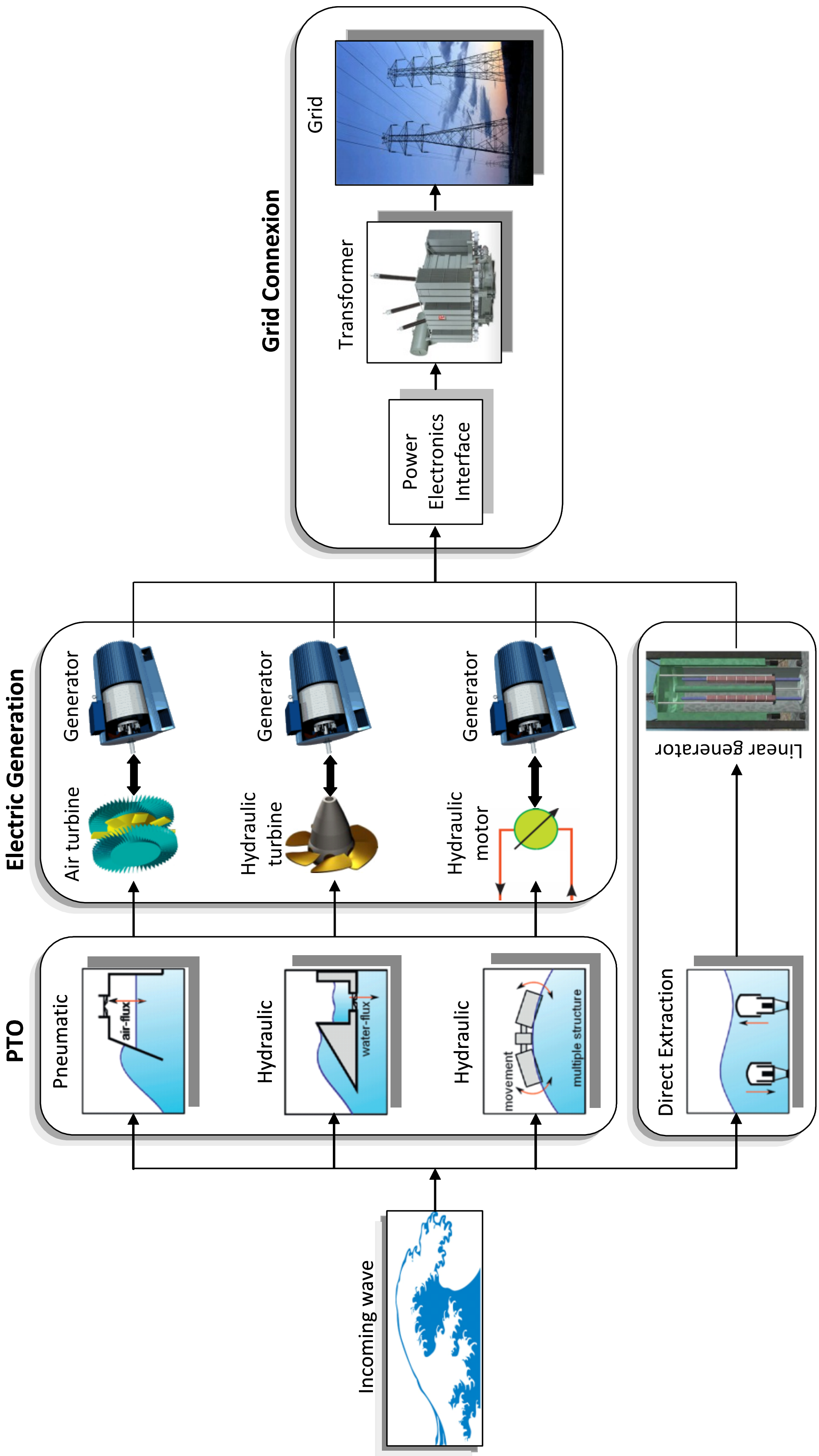


Fig. 8. WEC different type of conversions.

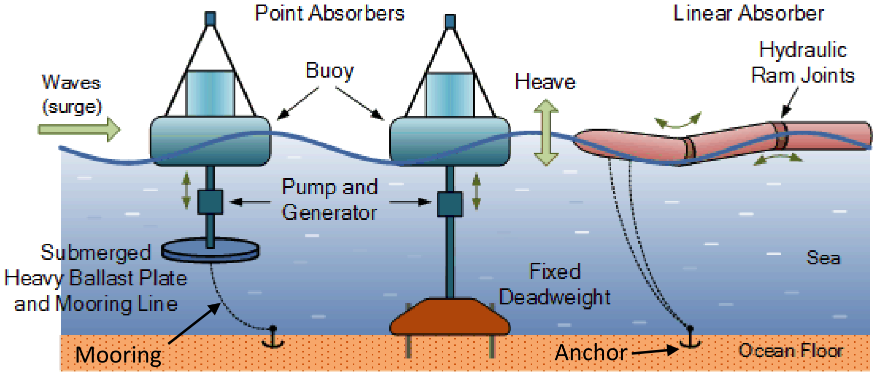


Fig. 9. Wave energy converters mooring and anchor.

TABLE 1. SOME WEC PROJECTS PTOS AND GENERATORS.

WEC	PTO	Generator
PELAMIS	Attenuator/Hydraulics	Cage induction generator
POWERBUOY	Point absorber	Permanent magnet synchronous generator
WAVESTAR [34]	Point absorber/ Hydraulics	Permanent magnet synchronous generator
SEAREV [5], [35]	Point absorber	Permanent magnet synchronous generator
BILBOQUET	Point absorber	Permanent magnet synchronous generator
OYSTER	Oscillating wave surge converter	Cage induction generator
LANGLEE [36]	Oscillating wave surge converter	Permanent magnet synchronous generator
LIMPET	Oscillating water column & Wells turbine	Cage induction generator
OCEANLINX	Oscillating water column & Denniss-Auld turbine	Cage induction generator
PICO [8]	Oscillating water column & Wells turbine	Doubly-fed induction generator
WAVE DRAGON	Overtopping & Kaplan turbine	Permanent magnet synchronous generator
SSG [37]	Overtopping	Permanent magnet synchronous generator
AWS	Direct drive	Linear permanent magnet generator

There are many kinds of connectors used on WECs and other marine structures [38], [42]. Anchors are the terminals that transfer the whole system forces to the seabed.

The two major requirements for a WEC mooring are to withstand the environmental and other loadings involved in keeping the device on station, and to be sufficiently cost-effective so that the overall device economics remain viable. In particular the mooring system is subject to highly cyclic, nonlinear load conditions, mainly induced by the incident waves.

Mooring systems, which may be suitable for WECs, can be categorized into two main configurations: spread mooring and single point mooring. Spread mooring restricts a WEC motion in the horizontal plane and hence will not allow it to weather-vane. This type of mooring may be appropriate for non-directional energy converters. Single point mooring allows a WEC to weather-vane [43-44]. There are several sub-types as listed in Table 2 and it is difficult to define which one is the best without considering the WEC type, location, safety, and cost [45-47]. However, it seems that Catenary Anchor Leg Mooring (CALM) in spread mooring, and Single Anchor Leg Mooring (SALM) in single point mooring are more popular in practical projects [48-49].

Figure 10 shows some commonly used mooring configurations.

V.1. Mooring Requirements

The mooring could not be considered as an additional cost item in the overall economics of a WEC. It should be designed as an integral element of the overall system that contributes to power extraction efficiency [50-52].

TABLE 2. MOORING TYPES.

Type	Spread	Single point
Sub-types	Catenary mooring	CALM
	Taut mooring	(Catenary Anchor Leg Mooring)
	Turret mooring	SALM
		(Single Anchor Leg Mooring)
		ALC
		(Articulated Loading Column)
		SPAR
		(Single Point Mooring & Reservoir)
		Fixed tower mooring

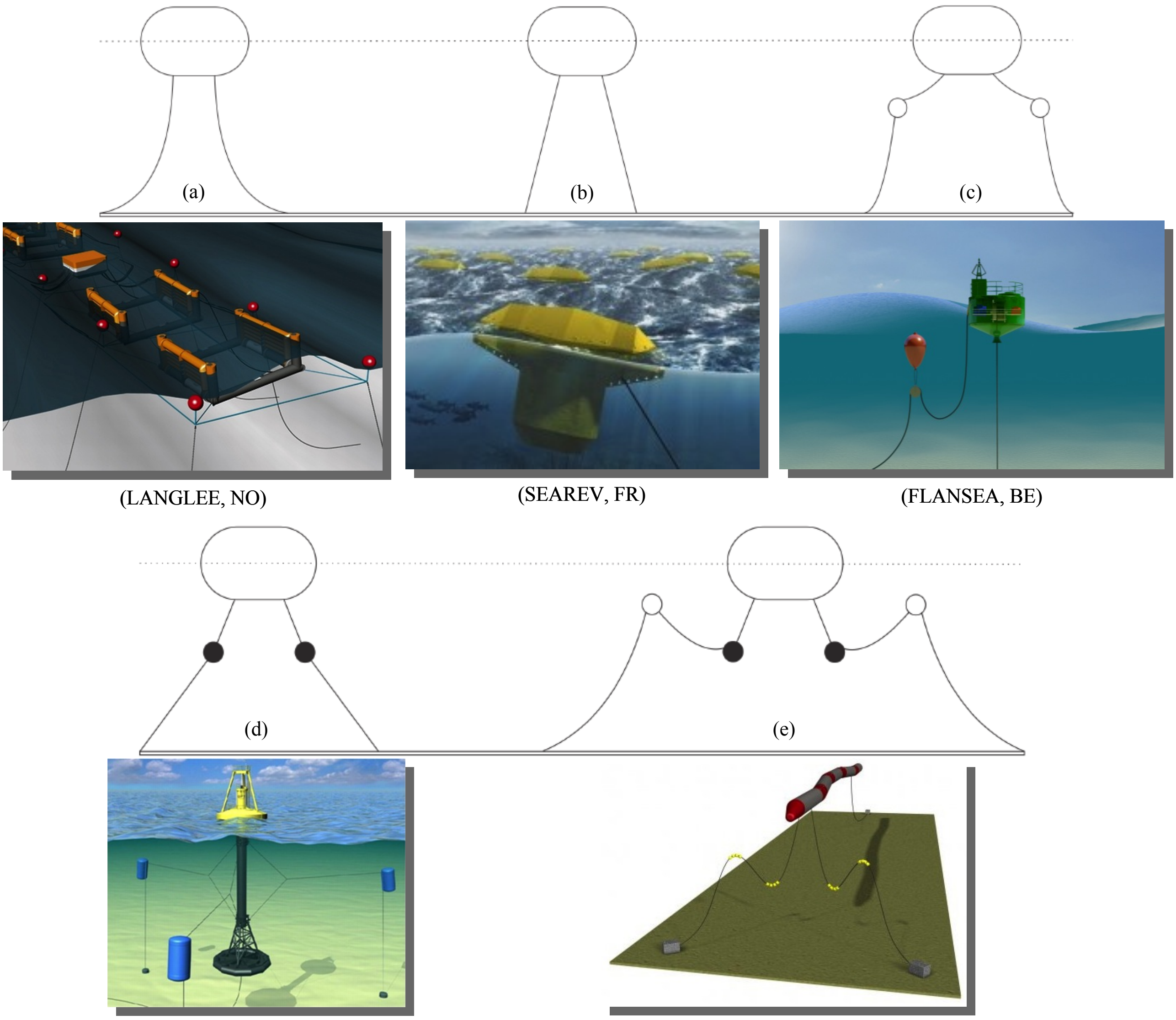


Fig. 10. Typical mooring systems for wave energy converters:
(a) Catenary line; (b) Taut line; (c) Taut line with mid-column float; (d) Taut line with weights, (e) Taut line with weights and floats.

In this context, the following list shows the main requirements that need to be considered for WEC moorings systems (a detailed list could be found in [41]).

- Mooring stiffness is an active element in the wave energy conversion principle used. The mooring system should be sufficiently stiff to:
  - ✓ Allow berthing for inspection and maintenance;
  - ✓ Station keeping within specified tolerances;
  - ✓ Maintain clearance distances between mooring;
  - ✓ Avoid constraints in lines and power cable in every tide conditions.
- It should be sufficiently compliant to the environmental loading to reduce the forces acting on anchors, mooring lines and the device itself to a minimum.
- It should be sufficient to accommodate the tidal range at the installation location.

It is therefore obvious that 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 [53].

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 [11], [54]. Indeed, it is difficult to follow what 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 [6].

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. Given the continuous environmental loading, fatigue has been identified as one of the key engineering challenges [55]. In addition, marine growth and corrosion need to be considered [56].
– Higher costs of construction, deployment, and maintenance need to be supported with substantial financial support from governments.

Regarding mooring fatigue and cost issues, it has been recently suggested to develop WECs without mooring [57-58]. The developed converter has station-keeping ability and evasive maneuver by diving. For station-keeping within a uniform bound, a wave glider has been adopted as propulsion system [59] (Fig. 11). In addition, such kind of system has the ability to submerge to a certain depth for its safety in emergency condition such as typhoon [60].

VII. Conclusion

This paper has proposed an up-to-date review of the most recent trends regarding main wave energy converter technologies with respect to overviews already published in the past years. In addition, mooring has been discussed and has been shown to be a key feature behind massive deployment of wave energy converters. Finally it has been highlighted some challenges that needs to be overcome to enlarge the vision of large-scale commercial arrays of wave energy converters.

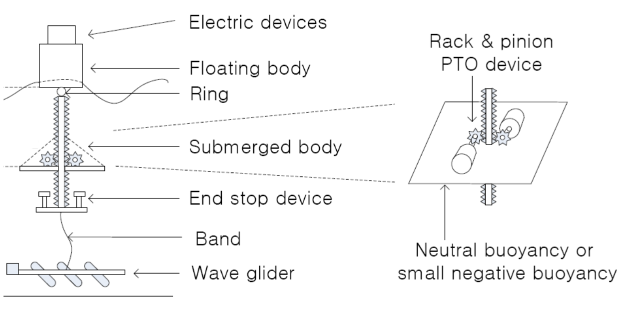


Fig. 11. A mooring-less wave energy converter concept [57].

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