

Ocean Wave Energy Conversion: A Review

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Abstract: The globally increasing demand for energy has encouraged many countries to search for alternative renewable sources of energy. To this end, the use of energy from ocean waves is of great interest to coastal countries. Hence, an assessment of the available resources is required to determine the appropriate locations where the higher amount of wave energy can be generated. The current paper presents a review of the resource characterizations for wave energy deployment. The paper gives, at first, a brief introduction and background to wave energy. Afterward, a detailed description of formulations and metrics used for resource characterization is introduced. Then, a classification of WECs (wave energy converters) according to their working principle, as well as PTO (power take off) mechanisms used for these WECs are introduced. Moreover, different sources for the long-term characterization of wave climate conditions are reviewed, including in situ measurements, satellite altimeters, and data reanalysis on one hand, and numerical simulations based on spectral wave models on the other hand. Finally, the review concludes by illustrating the economic feasibility of wave farms based on the use of the levelized cost of the energy index.

Keywords: wave energy; wave energy converters; wave energy indices; numerical wave models; resource assessment; levelized cost of energy



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1. Introduction

Ocean renewable energy resources are an emerging alternative to conventional fossil fuel resources (e.g., petroleum oil, natural gas, and coal), contributing, at the same time, to the energy independence of coastal regions. Among these resources, wave energy is considered the most promising, given its (i) highest power density of about 2 to 3 kW·m⁻², and, when compared to wind (0.4–0.6 kW·m⁻²) and solar (0.1–0.2 kW·m⁻²) energy densities, the mean wave power density is 10 times higher than that of wind and 100 times that of solar [1]. Moreover, wave energy is promising due to its (ii) predictability [2,3] and (iii) limited environmental and visual impacts [4]. Additionally, apart from energy production, coastal protection can be assured by using wave farms to restrict erosion processes [5,6]. Figure 1 presents the worldwide distribution of annual mean wave power density, with the indication of important wave directions as arrows. As indicated, the high energy zones are located between 40° and 60° in both the Northern Hemisphere (NH) and Southern Hemisphere (SH), with annual mean wave power values in the SH greater than in those in the NH, [7,8].

Wave energy depends on the geographical location and time [9,10]. The global wave energy potential in deep waters was evaluated in the range of 1 to 10 TW, which is significant for the universal power demand [11,12]. Although waves lose their energy when advancing from deep to shallow water waves because of phenomena like wave breaking and bottom friction [11,13], both offshore and nearshore areas were considered for wave

farms. Different WECs (wave energy converters) were designed and employed for wave energy extraction and transformation into electricity. These WECs were developed for specific properties, such as the following: different wave climate conditions, different locations, wave characteristics, and sea water depth.

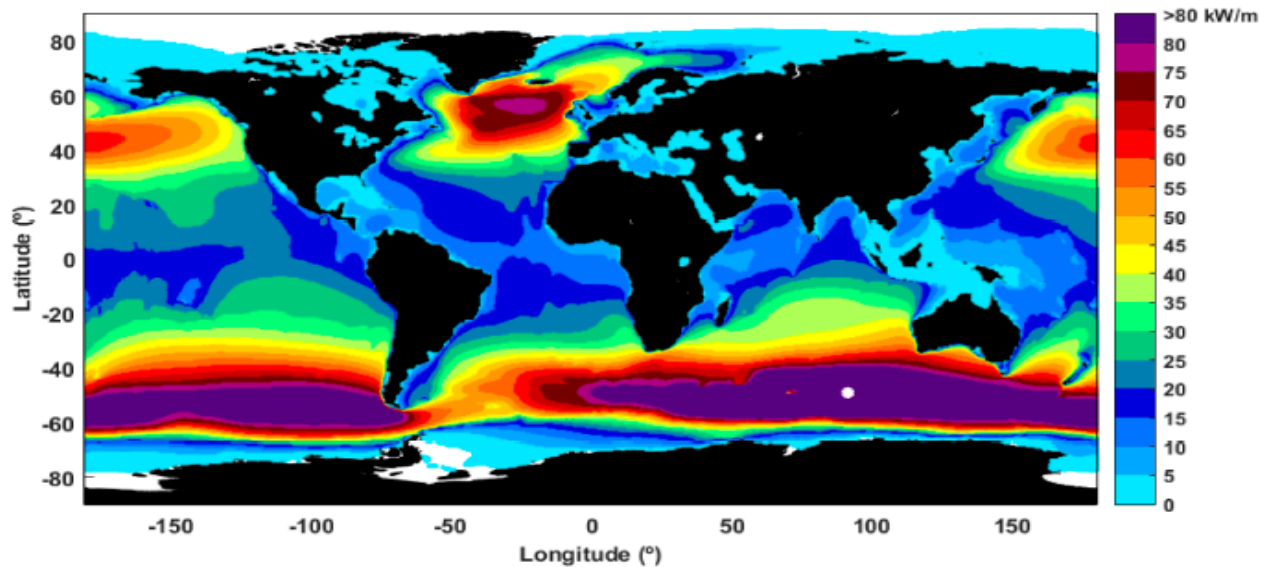


Figure 1. The worldwide distribution of the annual mean wave power in kW/m [8].

Therefore, an important step towards the setting up of a pilot plant for wave energy exploitation using WECs is the wave energy resource characterization. Studies on the assessment of available wave energy resources offer the possibility to identify the most energy-rich areas and quantify their wave energy, which is usually given as a function of the total annual mean wave power, and to describe this resource in terms of sea wave parameters, such as significant wave height, energy period, and mean wave direction [14]. An accurate estimate of available wave energy resources is needed in order to choose the appropriate WEC for a location of interest and tune an existing WEC design [15,16]. Similar to the wind industry, the wave energy distribution on a seasonal scale should cover a period of at least 10 years of historical records with at least three hours as a time step, as this will avoid the inter-annual fluctuations in sea waves [17,18]. Moreover, the resource should be described using the scatter diagram showing the bivariate distribution of the available wave energy as a function of wave height and energy period; this diagram would give an insight into the pairs of significant wave height and energy period that effectively contribute to the total energy. Another aspect to take into consideration is the resolution of the scatter diagram, as it must be the same or finer than the one of the used wave energy conversion system to identify its power output. In recent years, systems based on Artificial Intelligence have been used for wave forecasting based on several computing methods, including the following: Artificial Neural Networks (ANNs) [19], Bayesian Networks (BNs), Fuzzy Inference System (FIS), and Decision Trees (DTs) [20].

The current paper is organized as follows: Section 2 is devoted to the available sources used for long-term characterization and analysis of wave climate conditions at different scales and locations, including in situ measurements, satellite altimetry, and reanalysis archives. In Section 3, a critical comparative description of the existing spectral wave models is presented, complemented by a review of their applications for different areas around the world. The wave energy theories and their variability indices are introduced in Section 4, along with up-to-date State-of-the-Art sustainability metrics for the long-term characterization of wave energy. Then, Section 5 investigates the existing WECs, their classifications, and a summary of PTO systems integrated in WECs. In Section 6, the economic aspect of wave energy farms is discussed, introducing the *LCOE* (levelized cost of energy) index. Finally, the conclusions are listed in Section 7.

2. Available Wave Energy Resource Data

Several sources are available for long-term characterization and analysis of wave conditions at different scales and locations, including in situ measurements, satellite altimetry, and reanalysis archives. Each of these sources has its characteristics and is subject to some limitations. Satellite altimeters have huge spatial coverage of the ocean under a wide range of wave climate conditions [21], with low temporal resolution (e.g., daily), whereas in situ measurements are specific to particular oceanic areas and various ranges, in spite of having high temporal resolution.

The wave energy resource assessments were carried out using visual observations from buoys despite being restricted to local conditions [16]. Thereafter, wave energy assessments included buoy data combined with deep water spectral models to evaluate the offshore wave resources, overcoming the restrictions of the first assessments, that is, the limited period of measurement and the uncertainties linked to the extrapolation of local data to other sites [16]. As an example, Lenée-Bluhm et al. [22] utilized archived spectral registrations from ten buoys to evaluate and analyze the wave energy potential of the northwest United States. Wu et al. [23] used available data from six buoys to evaluate the seasonal variations in available wave power on the East China Sea. The characteristic of this method is that it can provide valuable sea state information with satisfactory accuracy when using precise and continuous buoy data. However, the quality and consistency of these estimations have been questioned in many research studies, as in [24].

Buoy systems are not widely available and do not have a large coverage area, essentially because of high costs and the difficulty related to harsh wave climate conditions [10]. For this reason, recent tools used satellite altimetry measurements for long-term global surveillance of the sea state [25,26]. Usually, wind and bathymetry data are used as input for such models. The typical output parameters are significant wave height, H_s , energy period, T_e , and mean wave direction. Assessments of wave energy resources were carried out at global [27,28], regional [29,30], and local levels. The accuracy of satellite measurements compared to in situ measurements from buoys around the globe were assessed in numerous studies [31–33]. According to Le Traon et al. [34], satellite altimetry provides precise observations on significant wave height with excellent coverage. However, the estimation of wave height is significantly less accurate in coastal and inland areas, mainly due to difficulties in estimating high-frequency atmospheric signals and mostly problems related to land contamination in radar altimeter footprints [35].

Until now, a number of satellite altimeters have been successfully operated by various international agencies (Table 1). They have offered a homogeneous, high-precision, and long-time series of observations, particularly over the ocean.

Table 1. Non-exhaustive review of satellite altimeters used for wave energy assessments.

Satellite Mission	Region	Exact Repeat Mission (Days)	Covered Period	Spatial Resolution	References
TOPEX/Poseidon	South China sea	10	2004	-	[36]
AVISO multi satellites merged altimeter data	Northwest Pacific	24	2009–2014	$1^\circ \times 1^\circ$	[37]
	China sea	24	2009–2013	$1^\circ \times 1^\circ$	[38]
ENVISAT	Indonesia	35	2002–2012	$1^\circ \times 1^\circ$	[39]
JASON-2	Andaman Sea Coast of Thailand	10	2014	-	[40]
SARAL/Altika	North of Scotland	35	2014	$11 \text{ km} \times 5 \text{ km}$	[41]
Multi-mission altimeter	Southeast Australia	-	1985–2020	$1^\circ \times 1^\circ$	[25,42]

Re-analysis data overcome the shortcomings of the above-mentioned methods regarding their higher temporal resolution of 1 to 6 h and their global spatial coverage. There are diverse wave data re-analyses with various spatio-temporal resolutions to be exploited for

wave energy assessment, such as CFSR (Climate Forecast System Reanalysis), HIPOCAS (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe), ECMWF (European Centre for Medium-Range Weather), NOAA (National Oceanic and Atmospheric Administration), NOGAPS (Navy Operational Global Atmospheric Prediction System), and NARR (North American Regional Reanalysis).

3. Spectral Wave Models

In recent years, third-generation wave models have been widely used for wave energy resource characterization, including global [7,15,43] to regional scales. These models include the following: WAM [44,45], WWIII model [46], SWAN [47], MIKE21-SW [48], and TOMAWAC [49]. The selection of a spectral wave model can be based on the area of interest, computational resource, type of study, etc. [50].

The fundamental similarity of these spectral wave models lies in the resolution of the balance equation with sinks and sources; however, differences in source terms of numerical implementation and parametrization of the physical processes were noticed. While WAM is built around one set of terms, WW3 and SWAN provide a variety of source terms and parametrization available for the user. WAM and WW3 were originally applied for wave prediction at oceanic scale or large areas, whereas SWAN is mostly used in the case of shallow water and coastal or small zones, apart few exceptions, e.g., [51]. For instance, Rute Bento et al. [52] evaluated the wave power in Galway Bay using WW3 for both wave generation and deep-water propagation and SWAN for shallow and intermediate sea wave propagation. Rusu et al. [53] described the development of a wave prediction system along the Iberian coast based on two wave models: WAM for the oceanic region and SWAN for the nearshore area. Nevertheless, WW3 and WAM models have been updated, adding new source terms and parametrizations to account for nearshore processes. As a result, all three models are suitable for wave energy simulation in coastal regions [45].

One of the major differences between the three models, SWAN, WW3, and WAM, is the numerical scheme used for the resolution of the action density equation. SWAN uses an implicit numerical propagation scheme, which enables much larger time steps for high computational efficiency rather than the restriction by stability criteria associated with explicit schemes in shallow waters. WW3 employed explicit numerical schemes; thus, the model time steps were limited by the CFL (Courant–Friedrichs–Lewy) stability criteria. Studies on model performance revealed that the two spectral models WW3 and SWAN can accurately forecast wave energy resource statistics and that their accuracy is highly improved by grid refinement [54,55]. Furthermore, these models can assess the spatial variation of sea wave characteristics at fine resolutions over vast areas covering different sea states, e.g., [55,56]. For instance, SWAN [57] supports an unstructured flexible mesh, providing an effective and feasible modeling approach of areas having complex geometries with many shoreline curves (i.e., major U.S. coastal regions).

According to [58], under extreme wave conditions, great differences are noticed among hindcasts at mid-high latitudes greater than 40° north, reaching 2.5 m, and a large area is concerned with differences above 2 m. A growing underestimation by WW3 compared to WAM when moving to harsh conditions was observed.

Table 2 gives non-exhaustive review of these different spectral wave model applications for wave energy assessment in different areas.

Table 2. Non-exhaustive review of spectral wave model applications for wave energy assessment in different areas.

Study Area	Authors	Spectral Models					Covered Period	Spatial—Temporal Resolutions	Main Results
		SWAN	WW3	WAM	MIKE21-SW	TOMAWAC			
Australia	Southeast Australia	[42]	X				40-year (1981–2020)	0.25° × 0.25°—1 h	Wave power in the western regions is between 30 and 65 kW/m, whilst less than 10 kW/m are found in nearshore areas of New South Wales, eastern Victoria, and northeastern Tasmania.
	Australian shelf	[59]	X				10-year (1997–2008)	0.1° × 0.1°—6 h	The southern Australian shelf is concerned with the greatest values of mean wave power 25–35 kW/m. Moderate values of wave power (10–20 kW/m) are found in New South Wales and southern Queens land shelves. For almost all the northern Australian shelf, wave power is below 10 kW/m.
	Southwestern coast of Australia	[60]	X				38-year (1980–2017)		Annual mean wave power is of 47.2 kW/m.
Spain	Death coast	[61]	X				44-year (1958–2001)		Annual mean wave power of about 50 kW/m.
	Galicia	[62]	X	X			9-year (1996–2005)	from 3° in the high seas to 0.25° (or 30 km) near the coastline—15 min	The annual mean wave power varies from ~15 kW/m to 50 kW/m.
	Canary Island	[63]	X	X			33-year (1979–2011)	0.05° × 0.1°—6 h/ 0.5° × 0.5°	Average annual energy availability of 25–30 kW/m.
	Menorca	[64]		X			17-year (1996–2013)	0.25° × 0.25°—1 h	The mean wave power of the most energetic area is reaching 8.9 kW/h. Lower mean wave power values (by about 5%) are obtained by comparing the results of this study with buoy data records.
	Lanzarote	[65]		X			44-year (1958–2001)	0.25° × 0.25°—3 h	The average wave power values exceeding 31 kW/h with more than 270 MW h/m of annual energy.
Black sea		[66]	X				20-year (1997–2016)	0.312° × 0.312°—3 h	Mean wave power values in the range of 2.5 to 3 kW/m.
		[67]	X				31-year (1979–2009)		The average wave power reaches higher values (about 10 kW/m) in the western region of Karaburun.

Table 2. Cont.

Study Area	Authors	Spectral Models				Covered Period	Spatial—Temporal Resolutions	Main Results
		SWAN WW3	WAM	MIKE21-SW	TOMAWAC			
China	Gulf of Beibu	[68]	X			34-year	$0.1^\circ \times 0.1^\circ$ —6 h	The highest wave energy flux is in the order of 1.5 kW/m.
	South China Sea	[36]	X			30-year (1986–2015)	$0.25^\circ \times 0.25^\circ$ —3 h	Annual wave energy density up to 65 kW/m.
Thailand	Gulf of Thailand	[69]	X			10 years (2004–2014)	$0.0167^\circ \times 0.0167^\circ$ —5 min	
	Andaman Sea	[40]	X			1 year	0.5° or ~ 55 km—3 h	The highest wave energy density (about 10.19 kW/m) is reached at the coastal area of Phuket Province.
Korea	Korean Seas	[70]	X			12-year (2007–2018)	$0.0625^\circ \times 0.05^\circ$ —1 h	Annual mean wave power values in the range of 0.6–13.3 kW/m in the Yellow Sea, 3–9 kW/m in Korea Strait, 3–8 kW/m in East Sea, and 7–12 kW/m in the vicinity of Jeju Island.
	Korean Peninsula	[71]		X		25-year (1979–2003)	$1/6^\circ$ or ~ 18 km	The annual mean wave power was found to be 11 kW/m in the southwestern side, 4 kW/m in the southern side, and 6 kW/m in the eastern side of peninsula.
Brazil	Alcatrazes island	[72]	X			14-year (2005–2018)	$1^\circ \times 1.25^\circ$	The annual mean wave power ranging between 2 and 17 kW/m.
	south-southeastern Brazilian Shelf	[73]			X	18-year (1997–2014)	30 arc minutes—3 h	The average wave power on Laguna, Ilhabela, and Farol Island is about 9.08 kW/m, 10.01 kW/m, and 15.93 kW/m, respectively.
	Coast of Santa Catarina	[74]		X		10-year (2004–2014)	$0.75^\circ \times 0.75^\circ$	The annual mean wave power at 20 m depth varies from 8 kW/m in sheltered zones to about 14.5 kW/m.
Italy	Sicily	[75]	X			11-year (1995–2005)	$1^\circ \times 1^\circ$ —3 h	The highest value of wave energy density 1240 kW/m is found at the Capo Gallo site while maximum energy values of 31.50 MWh/m correspond to Mazara del Vallo sites.
	Sardinia	[76]		X		20-year (1989–2009)	$1.5^\circ \times 1.5^\circ$ —6 h	The yearly offshore mean wave power varies between 8.91 kW/m and 10.29 kW/m.
Malaysia	East coast of Peninsular Malaysia	[77]	X			31-year (1979–2009)	~ 38 km—2 min	The annual average wave power for sites in the northern (southern) section of the coast ranges from 2.6 to 4.6 kW/m (0.5–1.5 kW/m).

Table 2. Cont.

Study Area	Authors	Spectral Models					Covered Period	Spatial—Temporal Resolutions	Main Results
		SWAN	WW3	WAM	MIKE21-SW	TOMAWAC			
United state	Hawaii	[78]	X				10-year	$1.25^\circ \times 1.25^\circ$ —3 min	The mean wave power ranges between 15 and 25 kW/m.
	California coast	[79]	X						
	GoM (Gulf of Mexico), East and West Coasts	[80]	X				36 years (1979–2015)	$0.167^\circ \times 0.167^\circ$ —3 h	The annual mean wave power values in most of the GoM sites are greater than 35 kW/m.
Portugal	Western Portuguese Coast	[81]	X				15-year (1995–2010)	$0.5^\circ \times 0.5^\circ$	Values of mean wave power in north and center west Portuguese coast varies from 28.11 kW/m to 30.90 kW/m, whereas the southwest coast wave power ranges between 21.51 kW/m and 22.96 kW/m.
India	Indian coast	[82]	X				19-year (2000–2018)	$0.1^\circ \times 0.1^\circ$ —6 h	The spatio-temporal variability analysis of wave energy flux reveals that southern coast of India has the mean wave energy flux ranging from 6 to 10 kW/m with a minimum monthly (<2.0), seasonal (<1.0), and annual (<0.2) variability.
	Indian shelf seas	[83]		X			34-year (1979–2012)	$0.75^\circ \times 0.75^\circ$ —6 h	The yearly average wave power available on the western shelf seas and along the eastern shelf seas of India is about 19.5 GW and 8.7 GW, respectively.
Scotland	Scottish coastlines	[84]	X				11-year (2004–2014)	$0.125^\circ \times 0.125^\circ$ —6 h	Annual mean wave energy of 75–80 kW/m
France	Western Brittany	[85]	X				27-year (1994–2020)	200 m—30 min	Wave energy flux exceeding 40 kW/m
	Franch Atlantic coast	[86]	X	X			33-year (1979–1989)	$0.0083^\circ \times 0.0083^\circ$	Annual mean wave power of 25–30 kW/m in the offshore western coast of France. In the nested zone, the mean wave energy values range from 8 to 10 kW/m around 40 km from the coastline, up to 15–20 kW/m in the southwestern region of the map.
	Western French coast	[16]	X	X			3-year (1998–2000)	$0.083^\circ \times 0.083^\circ$ —6 h	The annual wave power of 20 to 25 kW/m. A good agreement was obtained comparing the model and measured data from three buoys.

Table 2. Cont.

Study Area	Authors	Spectral Models					Covered Period	Spatial—Temporal Resolutions	Main Results
		SWAN	WW3	WAM	MIKE21-SW	TOMAWAC			
Iberian Peninsula	[87]	X	X				32-year (1979–2010)	$0.37^\circ \times 0.37^\circ$ —3 h	
Morocco	Atlantic coast of Morocco	[88]	X				30-year (1991–2020)	$0.25^\circ \times 0.25^\circ$ —6 h	Mean wave energy density is about 20 kW/m.
		[89]		X			44-year (1958–2001)		Average wave power varies between 28 and 30 kW/m.
Iran	Persian Gulf	[90]		X			30-year (1988–2017)	$0.125^\circ \times 0.125^\circ$ —6 h	The maximum mean wave power is approximately 0.33 kW/m at the southern Gulf, whereas the lowest value of about 0.08 kW/m is estimated in the Eastern Gulf within the Strait of Hormuz.
	Southern coasts of Iran, Persian Gulf	[91]	X				25-year (1984–2008)	0.2° (~20 km)—3 h	Annual average wave power below 2.73 kW/m.
Ireland	Aegean Sea	[92]			X		15-year (1999–2013)	0.125° —6 h	Annual average wave power greater than 8 kW/m.
Sweden	Baltic sea, Skagerrak and Kattegat area	[93]		X			16-year (1998–2013)	$0.01^\circ \times 0.02^\circ$ (~1.1 km)	The near-shore (<5 km from the coast) mean wave power is between 0 and 6.3 kW/m within the Swedish exclusive economic zone. At about 30 km from the coast, variations up to 7.5 kW/m are noticed.
Indonesia	Indonesia	[94]		X			6.5-year (2011–2017)	$0.05^\circ \times 0.05^\circ$ (~5.5 km)	The mean wave power is exceeding 30 kW/m in locations south of Jawa, Bali, and West Nusa Tenggara.
Chile	Central-South Coast of Chile	[95]	X				22-year (1989–2013)		Annual mean wave power 25–30 kW/m. Modeled data represent 10% compared to observed data.

4. Wave Energy Resource Assessment

4.1. Wave Power Calculation

The wave power per unit of the wave crest length, P , measured in kW per meter, can be evaluated using the following expression:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(\sigma) E(\sigma, \theta) d\sigma d\theta \quad (1)$$

where ρ is the seawater density, $g = 9.81 \text{ m}\cdot\text{s}^{-2}$ is the gravity acceleration, $E(\sigma, \theta)$ is the directional wave energy spectrum distributed over frequencies, σ , and direction of propagation of the spectral component, θ , and c_g is the group velocity.

In deep waters, the available wave power resource can be measured using two characteristic parameters: the significant wave height H_s (m) and the energy period T_e (s). Both are independent of the wave propagation direction. The significant wave height is approximately equal to the average height of the highest 1/3 of waves, and the energy period is defined as the period of a single sinusoidal wave that would have the same energy as the sea state [96,97]. Using deep water assumption, the wave power is estimated using the following expression [87,98]:

$$P = \frac{\rho g^2}{64\pi} \cdot H_s^2 \cdot T_e \quad (2)$$

Even though the energy period, T_e , could be modeled as illustrated in [99], in most cases, it is rarely specified, and it is estimated based on the peak period, T_p , and a calibration factor, α . This calibration factor is defined as $T_e = \alpha \cdot T_p$ and may have different values depending on the shape of the wave spectrum. Thus, α increases towards unity with decreasing spectral width [100] and $\alpha = 0.86$ for a fully developed sea in the case of the Pierson–Moskowitz spectrum, as mentioned in [74,101]. Conversely, for a JONSWAP spectrum with a peak enhancement coefficient of $\gamma = 3.3$, α reaches 0.90 [102,103]. This value was previously used in various studies [65,74,104–106].

Figure 1 presents the worldwide distribution of annual mean wave power density, with the indication of important wave directions as arrows. As indicated, the high energy zones are located between 40° and 60° in both the Northern Hemisphere (NH) and Southern Hemisphere (SH), with annual mean wave power values in the SH greater than in those in the NH [7,8].

4.2. Wave Energy Variability: Metrics and Indices

In addition to the amount of wave energy available in a specific site, another factor to take into consideration when selecting an area for the future exploitation of wave energy resources is its variability at different time scales (monthly, seasonal, and annual); it would be suitable to develop a wave energy project in an area with moderate and steady energy flux instead of an area with unsteady wave climate conditions since they are more reliable, report a higher efficiency, and maximize the performances of the harvesting devices. Several wave energy variability indices were introduced by [63,107] to characterize the variability of the resource at various time scales. Among these indicators, those suggested by [101] are employed: the coefficient of variation (cov), the seasonal variability index (S_v), and the monthly variability index (M_v).

The coefficient of variation (cov) is obtained from the standard deviation, σ , of the power time series $P(t)$ and the average value $\overline{P(t)}$:

$$cov = \frac{\sigma[P(t)]}{\overline{P(t)}} \quad (3)$$

Figure 2 illustrates the variation of the annual mean wave power as a function of the coefficient of variation, cov , for some specific countries around the world. As indicated, countries in the Northern Hemisphere (NH) are concerned with a greater variability com-

pared to countries in the Southern Hemisphere (SH) with about 1.5 in the North Atlantic, while in the SH, the cov values are, in general, lower than 1.

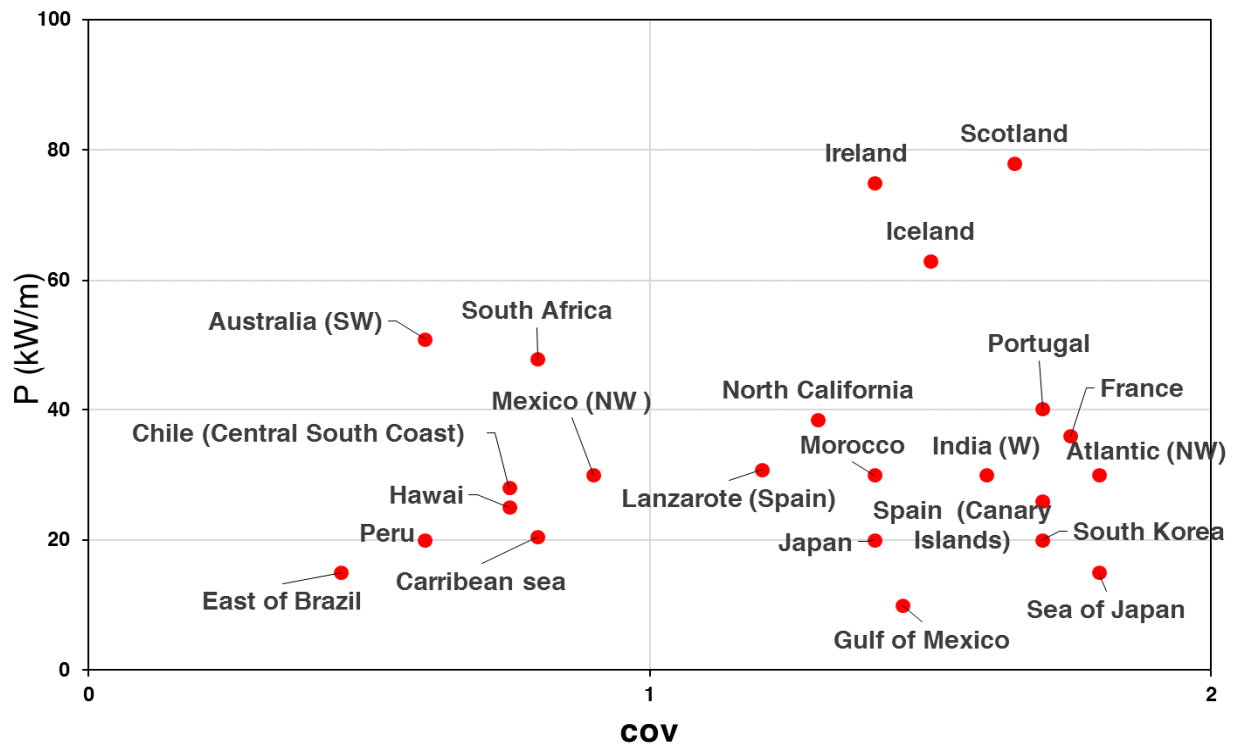


Figure 2. The mean wave power level versus the coefficient of variation *cov* for typical sites (data used in this figure are adapted from [2,108]).

The seasonal variability index (S_v) is defined as follows:

$$S_v = \frac{P_{S.max} - P_{S.min}}{P_{year}} \quad (4)$$

where $P_{S.max}$ is the average wave power density corresponding to the highest-energy season, $P_{S.min}$ is the average wave power density corresponding to the lowest-energy season, and P_{year} is the annual mean wave power (evaluated over the whole dataset). The greater the value of S_v , the larger the seasonal variability, with values lower than 1 indicating moderate seasonal variability.

The monthly variability (M_v) is defined as follows:

$$M_v = \frac{P_{M.max} - P_{M.min}}{P_{year}} \quad (5)$$

where $P_{M.max}$ is the average wave power density for the highest-energy month and $P_{M.min}$ is the average wave power density for the lowest-energy month. Obviously, the values of M_v are exceeding those of S_v .

Although M_v and S_v , define the short-term variation on monthly and seasonal scales, they do not take into consideration the long-term effect of climate change. In fact, a number of research papers showed that the assessment of wave energy and its temporal and spatial variation is not really sufficient for selecting the optimum sites for wave energy harvesting [109,110]. Within this regard, it was found that wave energy extraction in lower energetic areas that provide more stable conditions may be more efficient [111]. More recently, Kamranzad et al. [112] introduced an *OHI* (Optimum Hotspot Identifier) for determining the appropriate areas for wave energy harvesting applied to the Persian Gulf. This identifier enabled finding optimal locations based on three parameters: the

mean wave power, P_{mean} , the frequency, f , of occurrence for waves with power greater than a threshold specified by the authors ($P > 2$ kW/m for the Persian Gulf), and the previously cited monthly variability index M_v . The most suitable area was prescribed by the highest mean wave power and frequency but the lowest M_v . Thereafter, the OHI was used by García-Medina et al. [113] to identify the hotspots on the southern coast of Alaska. It was found that the Southeast Alaskan and the Aleutian Archipelagos have the most nearshore hotspots with $OHI > 5$ kW/m. Moreover, Martinez and Iglesias [114] developed and applied a new index, named WEI (Wave Exploitability Index), to compare mean and extreme wave heights. Alonso et al. [115] defined the $ETER$ (exploitation to extreme ratio) to quantify the effect of harsh wave climate conditions on the design and optimization of a WEC for local applications. In order to reduce the uncertainties and biases, Lavidas [98] suggested the $SIWED$ (Selection Index for Wave Energy Deployments). Additionally, Kamranzad and Takara [116] proposed a SI_p (Sustainability Index), in order to include the internal long-term change in wave energy in a specific region. Kamranzad and Mori [117] suggested a novel CSI (Climate Stability Index) that determines both short-term variations and long-term changes and helps define the stability in an area.

In addition to factors related to local sea state, such as the effect of climate change, exploitable storage of wave energy, accessibility, and availability, etc., the characteristics of WECs need to be considered in the prediction of power supply. For this consideration, Kamranzad and Hadadpour [118] proposed an MCA (Multi-Criteria Approach) that combines the above-mentioned factors to account for both WECs' performance and the sea state of the resource. The approach was applied in three hotspots of the seas surrounding Iran. Based on a comparison of the MCA index in the hotspots with eight types of WECs, the most suitable combination location/WEC was selected. The same approach was recently applied by Kamranzad et al. [119] to the southern coasts of China.

To summarize, the main indices used to take into account the long-term variations in wave climate conditions are given in Table 3.

Table 3. A non-exhaustive review of the resource-based indices for wave energy assessment.

Indices, Reference	Formula	Interpretation
OHI , [112]	$OHI = \frac{P_{mean} \cdot f}{M_v}$ Where M_v denotes the monthly variability, P_{mean} the mean wave power, and f the frequency.	Suitable areas are characterized by a greatest mean wave power and frequency but the lowest M_v .
WEI , [114]	$WEI = \frac{\overline{H_{RMS}}}{H_{max}}$ Where $\overline{H_{RMS}}$ is the mean value of the root-mean-square wave height, and H_{max} is the maximum individual wave height over the considered period.	Higher values of WEI , indicates that the area is suitable for wave energy exploitation.
$SIWED$, [98]	$SIWED = \frac{e^{-CoV_{H_{m0}} \cdot C_f}}{\frac{H_{EVA}}{H_{max}}}$ Where $CoV_{H_{m0}}$ the Coefficient of Variation, C_f the capacity factor, H_{EVA} the value of return waves based on extreme value analysis, and H_{max} the maxima value of wave height from the dataset.	Higher value of $SIWED$ means that both the area of study and the selected WEC have a better “match” and can provide reliable energy production.
$ETER$, [115]	$ETER = \frac{H_e}{H_d}$ Where H_e is the significant wave height representative of sea conditions with a maximum annual wave energy, and H_d is the significant wave height representative of the most severe extreme events that the project should be able to withstand.	$ETER$ corresponds to the structural efficiency of a WEC device. It is equal to the unity when exploitation and extreme conditions are the same. The lower this ratio is, the higher the gap between the operational and extreme conditions employed for a WEC design.

Table 3. Cont.

Indices, Reference	Formula	Interpretation
SI_p , [116]	$SI_p = \frac{P_{annual.mean}}{\max(P_{annual.mean})} \times \cos\left(\frac{\text{Rate of change}}{\max(\text{Rate of change})}\right)$ Where $P_{annual.mean}$ is the annual mean wave power. The dimensionless forms of $P_{annual.mean}$ and rate of change have been used by dividing them by their maximum value in the domain.	Higher values of SI_p result in higher wave energy potential, smallest rate of change in the long-term, and smallest monthly variability.
$WEDI$, [90]	$WEDI = \frac{P_{wave}}{J_{wave}}$ Where P_{wave} is the yearly mean wave power, and J_{wave} to the highest storm wave power.	$WEDI$ enables us to evaluate the potential hazards that could arise in terms of extreme conditions at WECs and offshore structures.
CSI , [117]	$CSI = \frac{X_H}{ (M_{vF} - M_{vH}) \times M_{vH} \times (X_F - X_H) }$ H and F denote historical and future periods, respectively, and X the yearly average value of each parameter.	Locations with higher values of CSI are those with higher stability in both short and long-term.
ST , [120]	$ST = \frac{P_{Mmin}}{P_{year}}$ Where P_{Mmin} is the mean wave power density in the minimum energy month kW/m and P_{year} is the annual mean wave power density over the covered period.	Higher values of ST indicate lower variations in the wave energy density.
MCA , [118]	$MCA = \left(\frac{\frac{E_e}{2000} \times \text{accessibility} \times \text{availability} \times \frac{E_0}{10,000} \times \frac{5}{H_{S-100}}}{M_{vE_0}} \right)$ With E_e the exploitable storage of wave energy per unit area, and H_{S-100}, the design wave height for 100-year return period.	The MCA accounts for the performance of systems in addition to the sea state and sustainability of the resources to identify the most suitable location for a wave energy project. It is useful for combined comparison of WECs and locations.

5. Wave Energy Conversion Technologies

Wave energy conversion systems convert the kinetic and/or potential energy from incident sea waves into useful mechanical or electrical energy that can be integrated into the storage or grid. The wave energy conversion chain for a WEC device is illustrated in Figure 3.

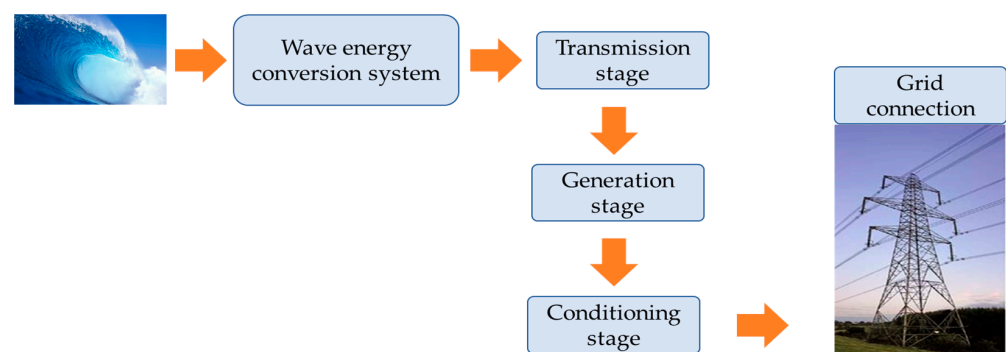


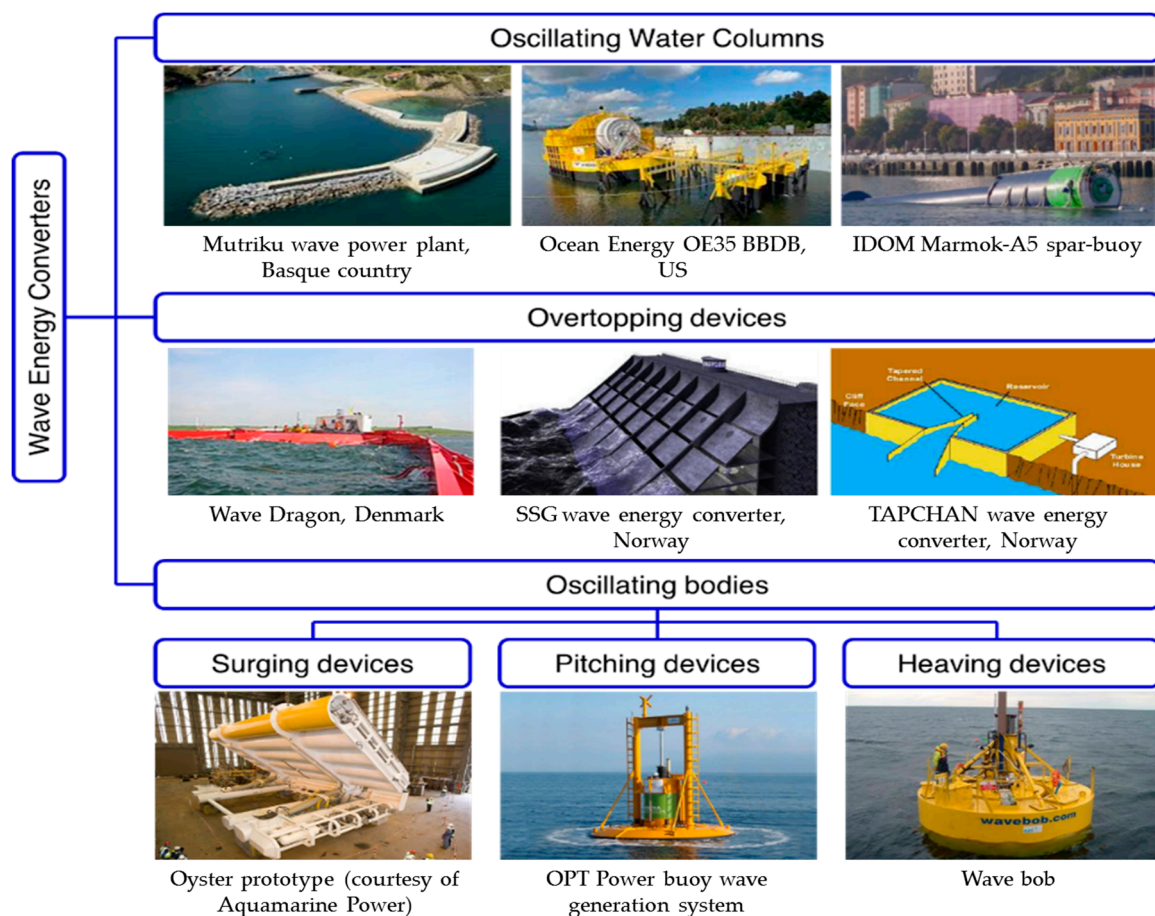
Figure 3. Illustration of wave energy conversion chain.

There have been a large number of wave energy conversion systems, resulting from the various ways of wave energy capture as well as the characteristics of the deployment location. Recent studies reported about one hundred systems at different stages of development [121,122]. Table 4 lists the installed capacity (kW) of wave energy conversion systems around the world since 2016, including the installed capacity for the following: planned projects, projects under development, and operational projects [123].

Table 4. Installed capacity of wave energy converters around the world since 2016 [124].

Country	Planned Projects (kW)	Installed (kW)	Operational (kW)	Total (kW)
Canada	0	0	11	11
New Zealand	0	20	0	20
Denmark	39	12	1	52
Italy	0	150	0	150
Mexico	200	0	0	200
Spain	0	230	296	526
Korea	0	0	665	665
China	0	400	300	700
Portugal	350	0	400	750
United States	1335	500	30	1865
Sweden	0	0	3200	3200
Ireland	5000	0	0	5000

In general, WECs can be classified according to their working principle, installation locations, operation mode, and design geometries [3,122,125–128]. According to their working principle, WECs can be classified into three distinct categories, namely, oscillating water columns (OWCs), overtopping devices, and oscillating bodies (also referred to as wave-activated bodies), as illustrated in Figure 4. These conversion systems can either be fixed or floating structures depending on the area in which they are placed (onshore or offshore).

**Figure 4.** Wave energy converters classified according to their working principle.

- Oscillating water columns: consist of submerged air chambers related to the atmosphere via a circular outlet inside which an air turbine is installed. The flow rate of air through the air turbine is created by the incoming waves that compress and de-

pressurize air in the chamber based on the periodic motion of the water's free surface. Electricity can be generated by connecting the air turbine to a generator. These systems are mostly integrated into breakwaters [129,130], such as Mutriku [131] operating for almost 10 years. However, there are concepts appropriate for deeper waters [127].

- Overtopping devices: are designed to capture the incident sea waves in a tank located above sea level, then they deliver the water back to the sea using a low-head turbine linked to a generator. These technologies can be placed onshore or offshore. Examples of such devices include TAPCHAN [132], SSG [133], and Floating Structure Wave Dragon [134].
- Oscillating body devices: are made from several components able to oscillate and move around a reference point. As the system is planted in the water, the sea waves start to excite the device. The energy is captured using the relative motion of the bodies. Examples of such devices include IPS buoy [135], Wavebob [136], Aquabuooy [137], Pelamis [138], SEAREV [139], Oyster [140], and oscillating buoy WEC [141].

The devices exemplified in Figure 4 are not intended to give an exhaustive list of existing WECs. They were chosen among prototypes or projects that were the object of extensive development efforts.

For all the wave energy conversion technologies, the power take-off (PTO) mechanism is the most important component, as it directly connects to the amount of the captured wave energy density into electricity. Many research works are actively working to develop and improve the PTO system, using various concepts [142–146]. The most common PTO mechanisms that can be used to convert the energy absorbed from sea waves by WECs into usable electricity are based on hydraulic systems, air turbines, direct electrical drive and direct mechanical drive (DMD) [122,147]. Figure 5 presents a schematic illustration of the commonly used PTO systems.

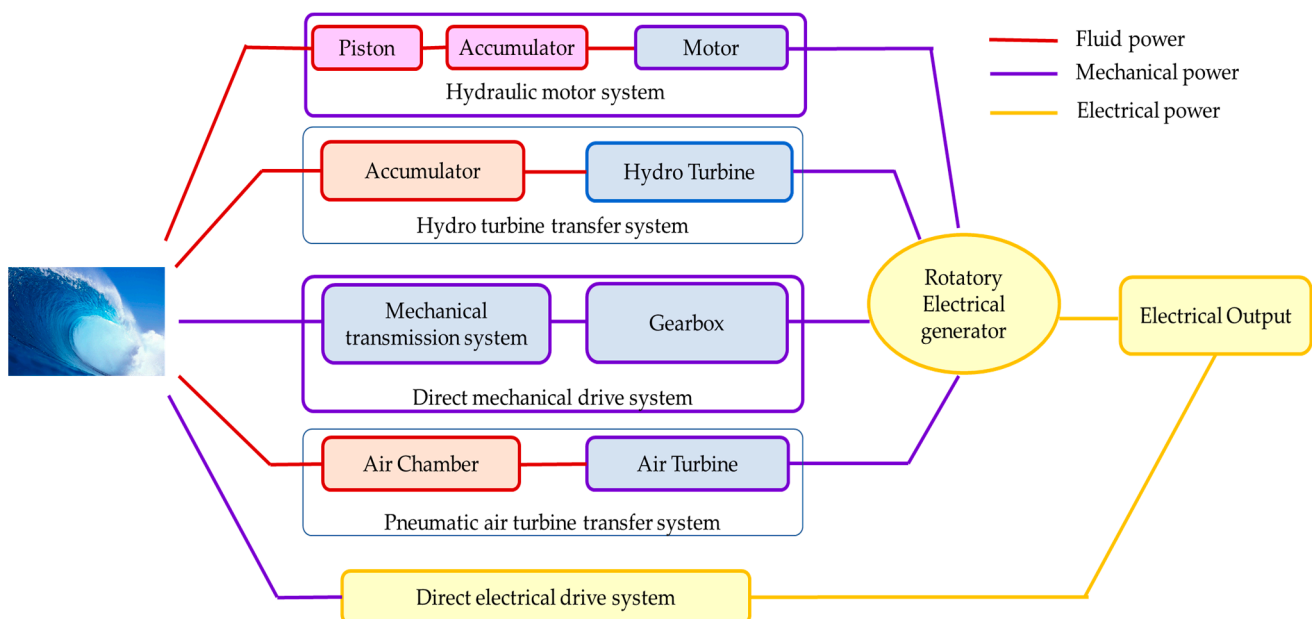


Figure 5. Power take-off systems for wave energy conversion technologies, adapted from [148].

Air turbines are commonly used as PTO systems in OWC devices [149–153], whereas hydraulic PTO systems or turbines are predominantly used for overtopping devices or oscillating bodies [139,154]. Direct-drive mechanical and electrical types of PTO mechanisms are used in the case of WECs that contain moving elements with relatively large dimensions and mass [155,156]. PTO mechanisms have to be adapted to be integrated into WECs, as the energy flow delivered by wave energy is random and highly variable. As a result, air turbines can only reach efficiencies of about 50 to 60%, while hydraulic turbines efficiencies

can reach about 70 to 90%. Examples of PTO systems integrated in wave energy conversion technologies are presented in Figure 6 and Table 5. The advantages and challenges of each kind of PTO system can be found in [122].

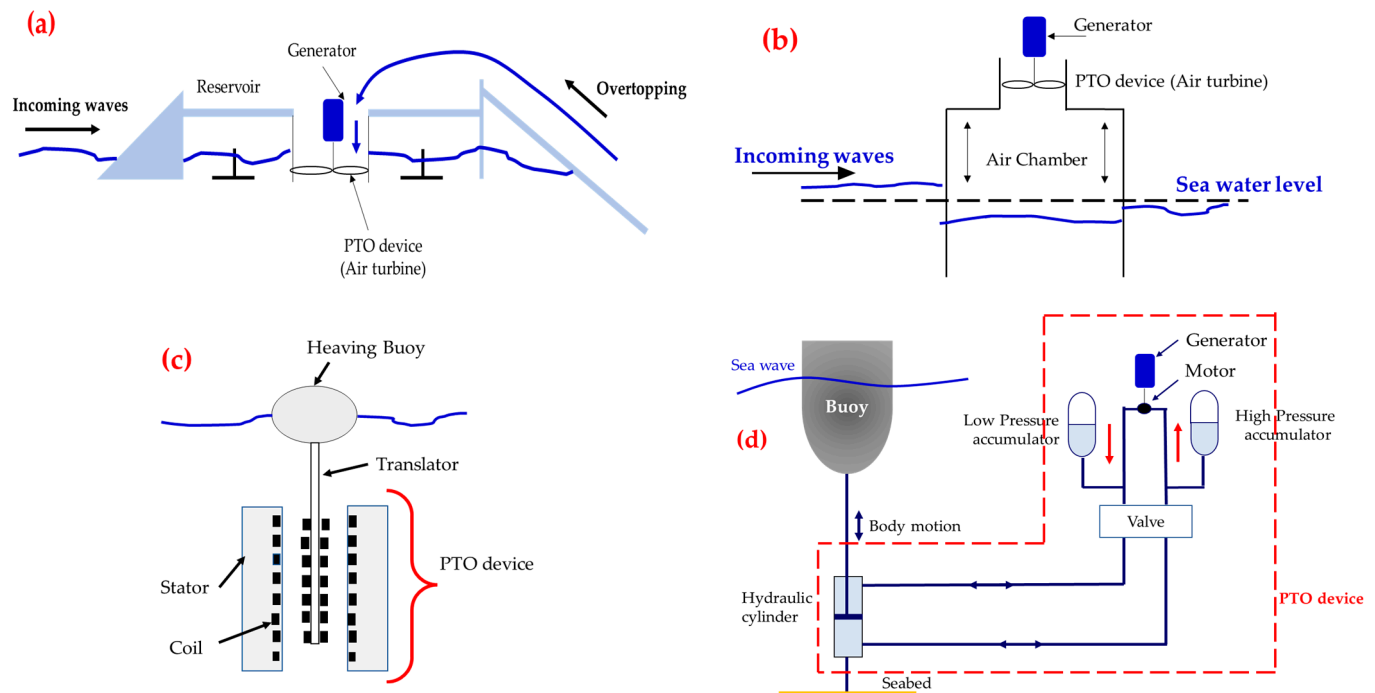


Figure 6. Examples of PTO mechanisms: (a) hydro turbine; (b) air turbine; (c) direct electrical drive PTO system; and (d) hydraulic.

Table 5. Examples of some wave energy converters with their power take-off (PTO) systems.

WEC Type	WEC Name	PTO	References
Oscillating Water Column	Pico	Wells turbine	[149]
	LIMPET	Wells turbine	[157]
	Mutriku	Wells turbine	[150]
	Sakata	Wells turbine	[158]
	Mighty Whale	Wells turbine	[159]
Oscillating bodies	Heaving system	Wave bob	[136,160]
		AquaBuOY	[97,161]
		IPS buoy	[135]
	Pitching system	Pelamis	[138]
		Oyster	[140]
		SEAREV	[139]

A prior characterization of wave energy resources is needed before any wave energy conversion technology implementation. Within this regard, extensive research on wave energy development indicates that WECs need to operate at an area with a minimum value of annual mean wave power estimated at 20 kW/m to be viable [15,127,154,162]. In addition to this condition, there are still many criteria to take into account in WECs' design stage, including survivability and reliability. In fact, in marine areas, WECs are subject to extreme wave conditions that surpass its operational thresholds and hence cause numerous failures like fatigue, corrosion, and extreme loads [163–165].

6. Wave Energy Production

In the last few decades, numerous studies were carried out to quantify the energy that can be generated if WECs are installed in marine areas [166–172]. Similarly, in the wind industry, where the potential of wind turbines takes into account the specific power curve in combination with wind measurements, the energy production of WECs in a particular area emerges from the combination of the power matrix of the wave converter (given by each WEC constructor either based on experiments or designed using numerical models) with the characteristic matrices of the wave climate at the same area. Legaz and Guedes Soares [173] used the power matrices of nine different WECs in order to evaluate their performances in the Bay of Cádiz. In reality, the compatibility between the sea states in the studied region and the power matrix of the WECs is of great importance in selecting the appropriate device. The power matrix consists of a bivariate distribution of sea conditions defined by H_s and T_e values (energy bins). The corresponding WEC yearly energy output, P_E , given in kWh, is calculated using the following equation [17,172]:

$$P_E = \frac{1}{100} \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} P_{ij} \quad (6)$$

where p_{ij} denotes the energy percentage corresponding to the bin defined by the j -th and column and the i -th row of the power matrix, while P_{ij} is the expected electric power output provided in the power matrix of the WEC for the same bin.

Given that the energy provided by WECs can considerably vary depending on the total power installed or size, it would be suitable to compare the normalized power performance using the capacity factor indicator, C_f . It compares the energy generated by a WEC during a specific period with the energy that can be generated if it has worked at maximum rated power. This parameter is expressed as the following:

$$C_f = 100 \frac{P_E}{N_p} \quad (7)$$

where P_E is the average electric power generated by each WEC in a particular area, while N_p denotes the maximum rated power of each device [17,174].

Within this regard, Rusu and Onea [5] assessed the performance of ten different WEC devices operating in different European coastal areas and found that the Pontoon Power converter has the highest value of the capacity factor of about 14.5% during the entire time and 21.1% during the winter time. Sierra et al. [64] evaluated the performances of three different WECs (Pelamis, AquaBuOY, and Wave Dragon) along the coast of Menorca, Spain. For the three devices, the capacity factors of 9%, 10%, and 11% are obtained, respectively. Lavidas and Venugopal [175] compared the performance of six wave converters for the Greek coastal regions. They found that the zones with the maximum capacity factors are located in both Crete Island and the southern Aegean Sea. Moreover, the Wavestar is noted as the best device, being able to operate at nominal power for low wave heights and periods. In western Brittany, Guillou and Chapalain [169] investigated the effect of temporal variability on the electricity production of three devices (Pelamis, AquaBuOY, and Wave Dragon). In winter, the WECs' performances indicated high variabilities with maximum monthly mean values of a capacity factor of about 65% for Wave Dragon. For the Croatian part of the Adriatic Sea, Pelamis wave energy converters are considered more suitable as they are concerned with higher capacity factor values [176]. Bozzi et al. [177] assessed the performance of several offshore WECs at a 10 km resolution along the Mediterranean coastline. It was shown that most of the Mediterranean coastline areas can be successfully exploited by downscaling (using the Froude Similarity Criterion) the existing wave energy conversion devices. More precisely, the capacity of six of the studied WECs is higher than 0.2 along 40% of the shoreline and exceeds 0.3 at 8% of the studied areas for three other WECs (AquaBuOY, Pelamis, and Wave bob). Martić et al. [178] analyzed and compared the performance of both full-scale and downscaled WECs in terms of operating hours

and capacity factor. They found that for the Adriatic Sea, the downscaled WECs are more suitable.

Table 6 gives the essential characteristics of certain wave energy conversion technologies in terms of the rated power, the recommended depth for installation, and the power matrix resolution. Another methodology for computing the power output for wave farms is presented in references [179–181].

Table 6. Non-exhaustive overview of WEC systems and their corresponding rated power and power matrix resolution, see [17,170,174,177].

WEC System	Rated Power (kW)	Recommended Depth	Power Matrix Resolution (H_s , T_e or T_p)	Reference
OWC	85	<20	1.0 m × 1.1 s	[172]
Wave dragon	5900	>30	0.5 m × 0.5 s	[182]
Wave Roller	1000	10–25	1.0 m × 1.0 s	[172]
Oyster	291	10–25	0.5 m × 1.0 s	[118]
OE (Ocean Energy buoy)	2880	>100	0.5 m × 1.0 s	[160]
Wave star C6	600	10–30	0.5 m × 1.0 s	[160]
AWS (Archimede Wave Swing)	2470	100	0.5 m × 0.5 s	[182]
Wave bob	1000	>50	0.5 m × 0.5 s	[160]
Pelamis	750	>50	0.5 m × 0.5 s	[182]
Oceantec	500	50–100		[183]
CETO	260	20–50	0.5 m × 0.5 s	[160]
Aquabuoy	250	>50	0.5 m × 1.0 s	[161]

Another important parameter to consider is associated with the energy capture and is often expressed as C_w (capture width). This parameter is defined as the ratio between P_E and P_w and is known as the width of the wave front from which all the absorbed power by the WEC can be extracted. The capacity factor is determined using the following equation [171]:

$$C_w = \frac{P_E}{P_w} \quad (8)$$

Although these power performance metrics are important in selecting the suitable WEC device for a particular region, the economic feasibility [184,185] is the most important aspect for WEC developers when determining whether an energy technology can reach commercialization [186]. In this context, the economic cost of a wave energy generation device incurred over its entire life cycle is evaluated using the *LCOE* index in Euro/MW h, which is widely reported in the literature [187–189]. According to Vanegas-Cantarero et al. [190], the *LCOE* can be calculated as follows:

$$LCOE = \frac{CapEx + \sum_{t=1}^n \frac{OpEx_t}{(1+r)^t}}{\sum_{t=1}^n \frac{AEP_t}{(1+r)^t}} \quad (9)$$

where n denotes the device's life expectancy in years, t is the year from the beginning of the project, and r is the discount rate (%), which accounts for the value of money as a function of time.

CapEx describes the total initial costs (here, units of \$).

CapEx describes costs (here, units of \$) of the WEC project's fixed assets, and *OpEx* includes ongoing costs (units of \$) for running the project throughout its lifetime, and AEP_t refers to the electricity generated by the project in year t .

$$AEP = PC \times C_f \times AF \times 8766 \text{ hour/year} \quad (10)$$

where PC is project capacity, C_f is the capacity factor, AF is the availability factor, and 8766 is the number of hours in a year, including leap years. The project capacity is defined

as the number of devices multiplied by the devices' rated powers (units of power, e.g., kW or MW). The availability factor is the "Availability of a wave energy converters to be in a state to perform a necessary function under given climate conditions at a given instant of time over a given duration, assuming that the necessary external resources are provided" [191,192].

It is useful to consider *AEP* as the product of (1) the power matrix of the WEC, (2) the joint occurrence frequency of H_s and T_e for a WEC deployment area, (3) the ability or inability of a WEC to operate in the wave conditions of the chosen area, (4) the percentage of time the device is operational, and (5) the total number of devices within the WEC array.

7. Conclusions

In the current paper, a detailed review was carried out on wave energy resource assessment tools and methods. The theoretical formulations used for wave energy density calculation as well as the indices for the short-term variability of wave resource were described. This section was complemented by a review of different metrics adopted to take into consideration both the long-term variability of the wave resource and the characteristics of WECs to account for in the prediction of power supply. Moreover, this paper highlights the available data for long-term characterization and analysis of wave climate including in situ measurements, satellite altimetry, and reanalysis archives. In fact, each of these sources has its characteristics and is subject to some limitations. Satellite altimeters have huge spatial coverage of the ocean under a wide range of wave climate conditions, with low temporal resolution (e.g., daily), whereas in situ measurements are specific to particular oceanic areas and various ranges in spite of having high temporal resolution. Re-analysis data overcome these limitations as they are of high temporal resolution of 1 to 6 h and global spatial coverage.

The existing numerical wave models and their area of application were presented. Also, the wave energy potential of each area was indicated to give developers an idea about the interesting locations for WEC deployment (Table 2). The results obtained from numerical wave models are usually calibrated with available data from satellite altimeters and buoys.

For wave energy exploitation, different WECs are presented. They may be classified according to their working principle into three distinct categories: (i) OWC (oscillating water column); (ii) overtopping devices; and (iii) oscillating bodies. For these WECs' implementation, a prior characterization of wave energy resources is needed. Extensive research on wave energy development indicates that WECs need to operate at an area with a minimum value of annual mean wave power estimated at 20 kW/m to be viable. Moreover, given that the energy generated by WECs can considerably vary depending on the total power installed or size, it is important to compare the energy generated by a WEC during a specific period with the energy that can be generated if it has worked at maximum rated power. Finally, a brief discussion of the economic feasibility of wave farms was provided based on the use of *LCOE* index. One of the challenges to address for future deployment and the commercialization of WECs is the survivability issue of these devices when experiencing extreme wave conditions.

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