Title	Wave exploitability index and wave resource classification
Author(s)	Martinez Diaz, Abel; Iglesias, Gregorio
Publication date	2020-12
Original citation	Martinez Diaz, A. and Iglesias, G. (2020) 'Wave exploitability index and wave resource classification', Renewable & Sustainable Energy Reviews, 134, 110393 (11pp). doi: 10.1016/j.rser.2020.110393
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://dx.doi.org/10.1016/j.rser.2020.110393 Access to the full text of the published version may require a subscription.
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Item downloaded from	http://hdl.handle.net/10468/13090

Renewable and Sustainable Energy Reviews 134 (2020) 110393

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Wave exploitability index and wave resource classification

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ARTICLE INFO

Keywords:
Wave energy
Wave power
Ocean energy
Marine renewable energy
Wave variability

ABSTRACT

The selection of areas for wave energy development requires a thorough characterisation of the resource. For all its importance, wave power should not be the only criterion, and overly emphasising its role to the detriment of other aspects may mislead developers to the wrong areas. In this work, a new approach is presented based on a combination of two elements: the Wave Exploitability Index (*WEI*), defined *ad hoc*, and a classification of the resource based on mean wave power. These elements are applied at a global scale using the ERA-5 database, which spans the period 1979–2019. The highest *WEI* values (0.14–0.22) are found to occur in the Tropics and mid-latitudes, which highlights their potential for wave energy exploitation. The lowest *WEI* values (below 0.06) are located in (semi)-enclosed seas, such as the Mediterranean Sea or the Gulf of Mexico. As regards the classification of the resource, Classes IV and V, with mean wave power over 40 kWm^{-1}, occur in areas which have aroused great interest but which often do not have high *WEI* values due to the resource variability (e.g., Western Europe); these areas are hardly ideal from the resource standpoint. Class I (below 10 kWm^{-1}), typical of enclosed seas, is of little interest. Finally, Classes II and III (10–40 kWm^{-1}) occur in areas open to the ocean in the lower and lower-middle latitudes (e.g., Chile, SW Australia); they present the highest *WEI* values, thus showing great potential, and have received scant attention so far.

1. Introduction

Ocean energy is among the renewable energies with the greatest potential for development [1]. Both academia and industry have dedicated intensive efforts to developing technologies to harvest ocean energy, especially wave and tidal energy. A number of research works have focused on the development and improvement of technological solutions to extract the power of the waves, or wave energy converters (WECs) [2], and their deployment in arrays, also known as wave farms [3–7]. Efforts have also been devoted to the characterisation of the wave energy resource [8–17] and the impacts of climate change [18] – a fundamental aspect for the successful exploitation of wave energy. However, despite the fact that these lines of research are inherently related [19], these works have often been presented as independent. It is necessary to bear in mind that the ultimate goal of the resource assessment is the development of wave energy in a particular region. In this sense, there is not a universal criterion or benchmark to characterise the wave energy resource.

Several authors have previously addressed the global wave energy resource, using different models and databases [20–28]. While the first works typically cover short timespans, often less than 10 years [20–23], the recent appearance of larger datasets covering several decades allows the study of the interannual and long-term trends in the assessment of the global wave energy resource [24,26]. A thorough overview of long-terms predictions of wave energy is reported in Ref. [29]. Trends in the global wave energy resource are investigated in Refs. [30], and a recent increase in the global wave power (0.4% per year) is found to be induced by upper-ocean warming resulting from climate change.

In this work a new classification of the global wave energy resource is presented. This classification is key for the exploitation of the resource in real-life scenarios; it provides a framework for global strategies and energy policies, and for the standardisation and subsequent optimisation of wave energy converters. A resource classification along similar lines is already available for other forms of renewable energy, most notably, wind [31], but not yet for wave energy.

The assessment of the global energy resource in this work is based on the up-to-date ERA-5 reanalysis database [32], covering a more recent period than other works, from 1979 to 2019 (40 years). This overcomes one limitation of previous works, based on outdated data. In addition, it provides a new contribution to the assessment of global wave energy and its variability – including its seasonality.

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https://doi.org/10.1016/j.rser.2020.110393
Received 25 March 2020; Received in revised form 25 July 2020; Accepted 20 September 2020
Available online 24 September 2020
1364-0321/

Nomenclature

COV	Coefficient of Variation
DJF	December, January, February
ECMWF	European Centre for Medium-Range Weather Forecast
H_{max}	Maximum individual wave height
H_{rms}	Root-mean-square wave height
H_s	Significant height of combined wind waves and swell
JJA	June, July, August
MAM	March, April, May
P	Wave power
SON	September, October, November
T_e	Energy period
T_p	peak wave period
WEC	Wave energy converter
WEI	Wave Exploitability Index
$\bar{x}$	Mean value of the statistical sample
σ	Standard deviation

In fact, the limitations of the conventional approach have become apparent in the recent literature, with a number of papers showing that the assessment of wave energy and its temporal and spatial variation are not sufficient for the selection of optimum locations for wave energy exploitation. More specifically, it has been found that wave energy extraction in less energetic locations but offering more stable conditions may be more efficient [33]. Other variables, such as accessibility and sustainability, have been found to play a significant role in the selection of future locations of wave energy exploitation [34,35].

Therein lies the motivation for introducing in this work the new Wave Exploitability Index (*WEI*). The *WEI* uses the maximum and mean root-mean-square wave heights of a site, based on a database spanning 40 years, as proxies for the cost of a wave farm and the income that can be obtained from its electricity production, respectively.

The introduction of the Wave Exploitability Index (*WEI*) provides a new approximation to the attractiveness of an area for wave energy exploitation. The conventional approach is based primarily on the average wave power. By contrast, the novel approach presented in this work is based on the Wave Exploitability Index (*WEI*) and a new classification of the resource. This novel approach is shown to be useful in that it highlights the resource downsides of areas that have received great attention (e.g., Western Europe) and, perhaps most importantly, helps identify areas of interest for the development of wave energy which have been overlooked so far (e.g., Chile, Southwest Australia).

This paper has three main objectives. First, to present a new global resource classification, along the lines of classifications that exist for other renewable resources (most notably, wind) but not yet for wave energy. Second, to develop and apply a new index, named Wave Exploitability Index (*WEI*), to help in selecting potential development areas. And, finally, to prove the usefulness of these new tools – the global resource classification and the *WEI* – by applying them in a global case study.

The paper is organised as follows. First, Section 2 describes the materials and methods used in this work. Section 3 presents the new classification of the global wave energy resource. The variability of the global wave energy resource is assessed in Section 4. Section 5 introduces the new Wave Exploitability Index (*WEI*), which is evaluated globally. In Section 6, the results are thoroughly analysed and discussed. Finally, conclusions are drawn in Section 7.

2. Materials and methods

2.1. Data

The data used in this work were obtained from the ERA-5 wave reanalysis database of the European Centre for Medium-Range Weather Forecast (ECMWF) [32]. The ERA reanalysis merges data from historical observations and forecasts to provide an accurate evolving state of the atmosphere and the surface over the last few decades At the time this work was carried out, the data available included atmospheric and ocean reanalyses spanning 40 years, from 1979 to 2019, which are continuously updated. When complete, ERA-5 will contain data of the global atmosphere and surface from 1950 onwards.

More specifically, the data employed in this work are the significant height of combined wind waves and swell (H_s), the peak wave period (T_p) and the maximum individual wave height (H_{max}), with a spatial resolution of 0.5 × 0.5° and a time resolution of 3 h.

2.2. Methodology

The wave power for irregular waves may be computed from the spectral energy density function $S(f)$, where f represents the frequency. Typically, the spectral shape of the energy function is described by the characteristic wave parameters, i.e., the significant wave height H_s and the energy period T_e. Assuming a Rayleigh distribution of the wave heights, the significant wave height can be expressed [8] as

$$H_s = 4.004\sqrt{m_0} \approx 4\sqrt{m_0}, \tag{2}$$

where m_0 is the zeroth-order moment of the variance spectrum [36],

$$m_0 = \int_0^\infty S(f)df. \tag{3}$$

Although the significant wave height is the most commonly used parameter, in certain applications it is preferable to use the root-mean-square wave height (H_{rms}), which is the wave height of a sinusoidal wave with the same energy density as the sea state. Assuming a Rayleigh distribution, its relationship with the significant wave height [37] is

$$H_s = \sqrt{2}H_{rms}. \tag{4}$$

The energy period (T_e) can be interpreted as the period of a sinusoidal wave with the same wave energy flux as the sea state in question. It can be expressed [6] as

$$T_e = \frac{m_{-1}}{m_0}. \tag{5}$$

Assuming a JONSWAP spectrum [38], the energy period may be approximated [7] as

$$T_e = 0.9T_p. \tag{6}$$

Assuming a Rayleigh distribution of wave heights, wave power can be expressed as a function of the significant wave height and the energy period [7],

$$P = \frac{\rho g^2}{64\pi}T_e {H_s}^2, \tag{7}$$

with P the wave power or wave energy flux per unit width of wave front, g the acceleration of gravity and ρ the sea water density, which is assumed to be $\rho = 1025$ kg m^{-3}. Wave power can be expressed in terms of the root-mean-square height by combining Eqs. (4) and (7):

$$P = \frac{\rho g^2}{32\pi}T_e {H_{rms}}^2. \tag{8}$$

The accurate estimation of the wave power will depend to a great extent on wave heights being Rayleigh distributed, with possible inaccuracies in the period playing a lesser role given the quadratic exponent of the significant wave height in Eq. (7).

3. Global classification of the wave energy resource

Using the data from Section 2.1 and the formulation from Section 2.2, the values of the mean significant wave height and energy period (Eq. (6)) were obtained (Figs. 1 and 2, respectively). The ERA-5 reanalysis does not provide data in the vicinity of the Arctic and Antarctic Circles, where an ice sheet is present during part of the year, thus precluding the installation of WECs. In the figures these areas are represented in white. With the values of significant wave height and energy period, the global mean wave power (Eq. (7)) was calculated (Fig. 3). The results indicate that the mean wave power available to be harvested presents a substantial spatial variability, with the greatest values located in the upper-mid-latitudes (40° to 60°) bands of the Northern and, especially, Southern Hemispheres. This is due to the absence of land masses, which creates an ocean (the Southern Ocean) that circumambulates the Earth uninterrupted. Within the Southern Ocean the tip of South America creates an area of slightly lower wave power to its east, so that the Atlantic section of the Southern Ocean is slightly less energetic than its Pacific and Indian counterparts.

The high wave power band in the upper-mid-latitudes is also present in the Northern Hemisphere, albeit with smaller values due to the presence of the continental masses, which result in shorter fetches. Interestingly, the Northeastern Atlantic stands out in relation to the Pacific. This is due to the strength of the two centres of action that govern the atmospheric circulation in this region: the Iceland Low and the Azores High. Mean wave power is weaker in the lower-mid and, especially, low latitudes. Within this band the Pacific Ocean stands out thanks to its longer fetch.

The scatter plots of significant wave height (Fig. 4a) and wave power (Fig. 4b) of the nodes in the 0.5° × 0.5° grid are also relevant to characterising the global resource.

The classification of the wave energy resource proposed in this work is based on the mean wave power (Fig. 3), which is arguably the single most reliable metric of the resource, and directly related to the power output of a WEC. Based on the power matrices for different WECs [39, 40], the information in Fig. 4b and the global map, which will affect directly the possibility of harvesting this energy, the wave energy resource is classified by considering different ranges of the mean wave power (Table 1), from Class I to Class V, with Class I corresponding to the lowest values and Class V to the highest. The ranges of the energy period and the corresponding significant wave height values of each class from Fig. 4 are also shown in Table 1. Accordingly, five locations (Fig. 6) have been selected as characteristic of each class (Table 1). The wave resource classes are depicted in the global map (Fig. 5), and certain areas of interest are shown in the regional maps in Fig. 6.

In this classification, the least energetic category (Class I, or *Mediterranean*) corresponds to values of wave power below 10 kWm^{-1} – hardly of interest for energy harvesting. Waves in this range (Table 1) have significant wave heights below 1.4 m and energy periods typically in the range 3.5–6 s (Fig. 4). This class is characteristic of enclosed and semi-enclosed seas with a small to medium fetch, e.g., the Mediterranean (Fig. 6a), Baltic, Black and Red Seas (Fig. 5) or the Gulf of Mexico.

Albeit slightly more energetic, with mean wave power values in the range 10–20 kWm^{-1}, Class II, or *Arabian*, has still a limited resource. It occurs primarily in tropical seas, generally more open to the ocean than their Class I counterparts but still largely surrounded by land masses, which limit the fetch, e.g., the Caribbean, the Gulf of Guinea, the Arabian Sea (Fig. 6b) or the Gulf of Bengal.

Class III, or *Hawaiian,* has mean wave power values in the range 20–40 kWm^{-1}, clearly of greater interest for wave energy exploitation. Whereas classes I and II are composed by low-period sea states, with energy periods typically between 4 and 9 s (Fig. 4b), Class III is composed primarily of longer periods. This is due to the fact that, unlike Classes I and II, Class III occurs mainly in open ocean locations (with a long fetch). As regards latitudes, Class III is typical of low and lower-middle latitudes (Fig. 5), both in the Central and Eastern Pacific (Fig. 6c) and in the Central Atlantic (Fig. 6a).

Class IV, or *North Atlantic,* has mean wave power values in the range 40–80 kWm^{-1}. Like Class III, it corresponds to open ocean areas,

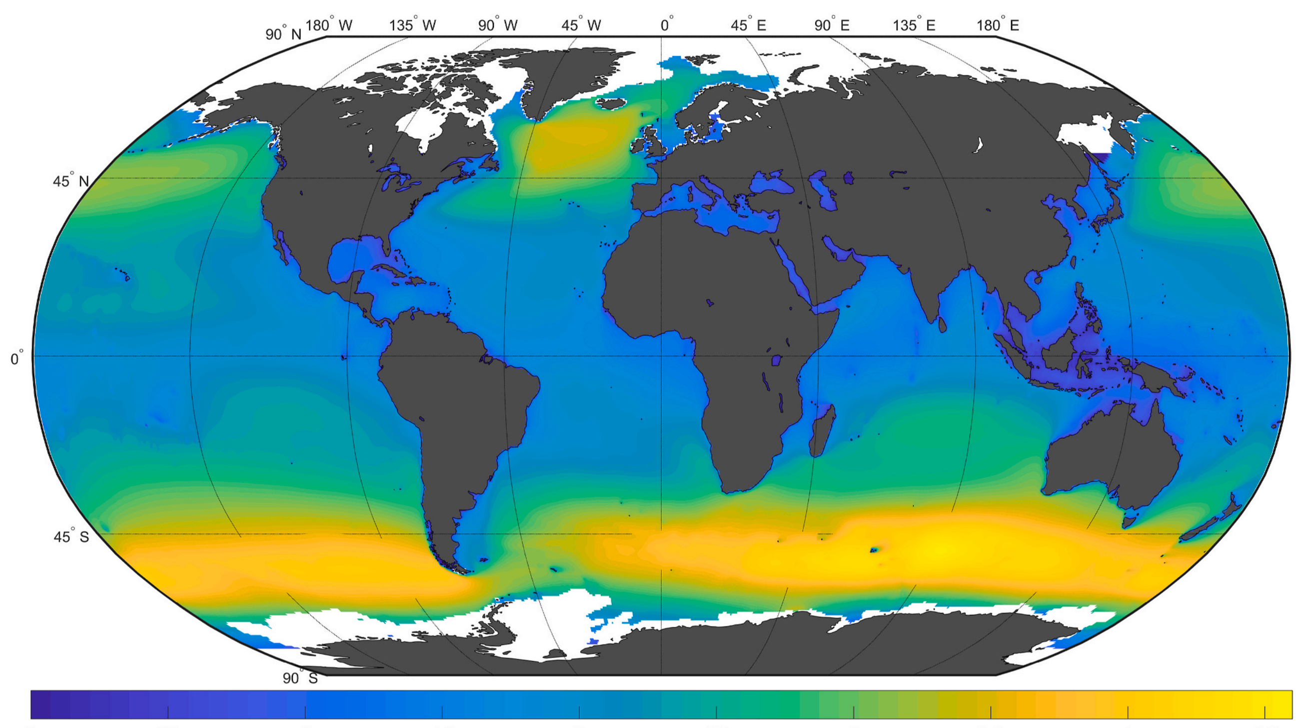

Fig. 1. Global mean value of the significant wave height, H_s (m).

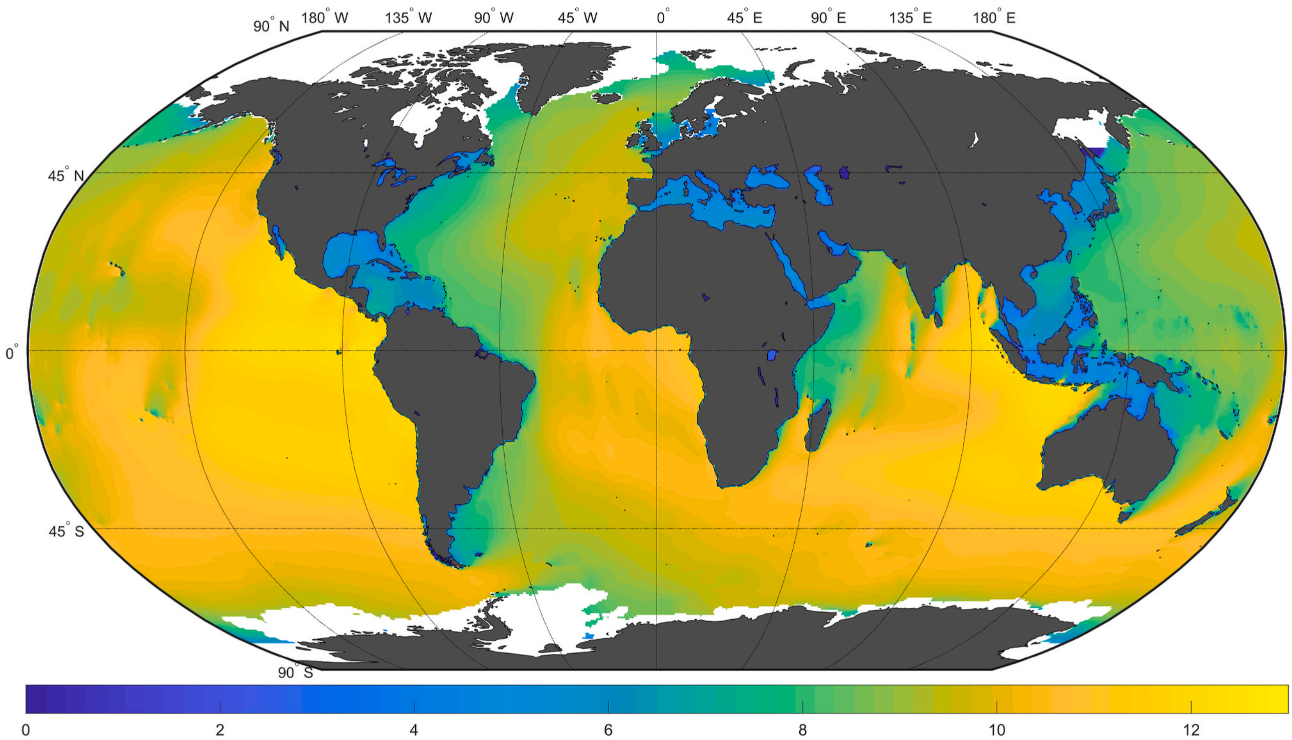

Fig. 2. Global mean value of the energy period, T_e (s).

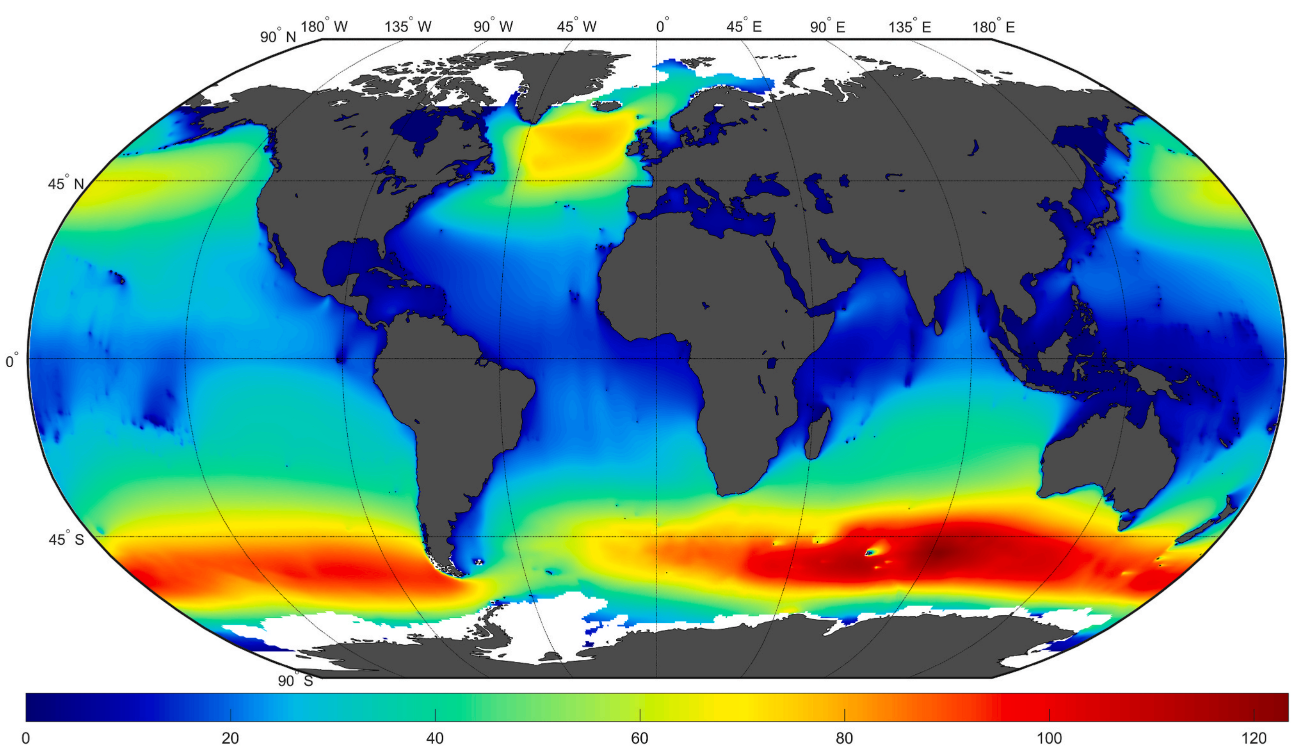

Fig. 3. Global mean value of wave power, P (kWm).

implying long-period sea states. The difference between Classes III and IV is in the latitudes – Class IV occurs chiefly in upper-middle latitudes, where the ocean swells are energised by the prevailing westerly winds and the associated cyclones – which ultimately explains the greater resource. Typical areas are, e.g., the North Atlantic and the North Pacific. Class IV occurs close to the coast, and therefore in water depths suitable for the development of wave farms, off Western Europe (Fig. 6a), the West Coast of North America, the Chilean Coast and Australia. Due to the substantial resource and the population density, a number of researchers investigated the wave resource in Western Europe, notably in Ireland, Scotland, Spain and Portugal [13,41–45].

Finally, Class V, or *Southern Ocean*, has mean wave power values over

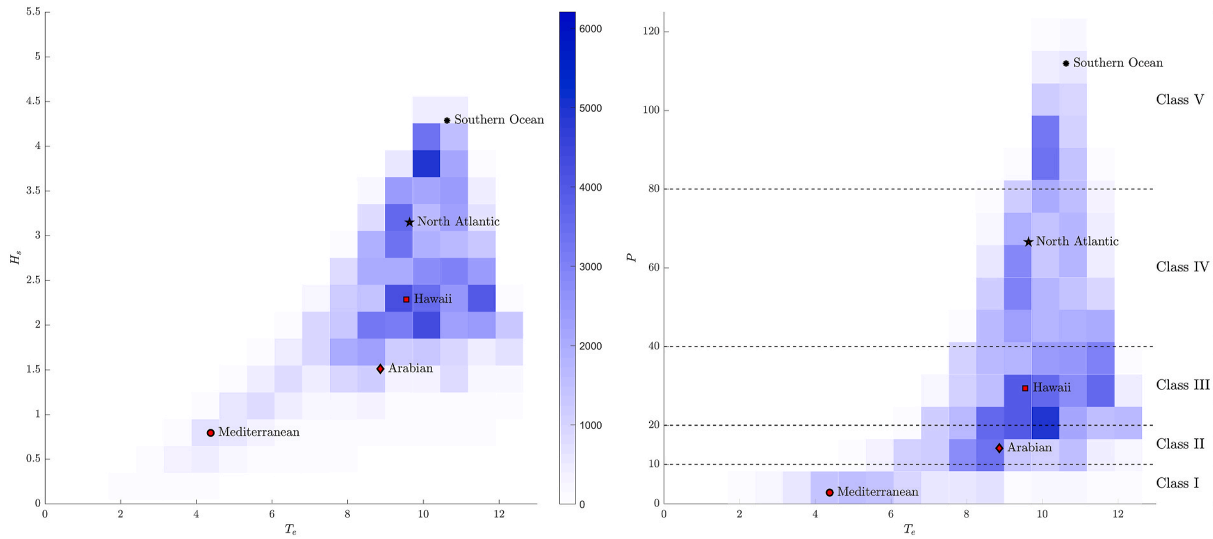

Fig. 4. Global scatter diagram of significant wave height vs. energy period (a), and wave power vs. energy period (b). The intensity of the colour indicates the density of points, with all the points in the global 0.5° × 0.5° mesh represented. The isolines of power in the right-hand plot (b) delineate the classes proposed (Table 1). The points depicted correspond to the five points designated as representative of their respective Wave Resource Class (Fig. 6). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Classification of the wave energy resource based on mean wave power (P), with corresponding ranges of significant wave height (Hs), energy period (Te) (Fig. 4) and maximum individual wave height (Hmax).

Wave Resource Class	$P (kWm^{-1})$	H_s (m)	T_e (s)	(m)	Typical of
I (Mediterranean)	<10	<2	1.7–12.6	<24.8	Enclosed and semi-enclosed seas
II (Arabian)	10–20	1.5–2.5	5.0–12.6	5.2–30.6	Tropical seas
III (Hawaiian)	20–40	2–3.3	6.3–12.6	6.4–31.8	Oceans (mid & lower-middle latitudes)
IV (North Atlantic)	40–80	2.8–4.2	7.8–12	11.2–36.7	Oceans (upper-middle latitudes)
V (Southern Ocean)	>80	>3.8	9–11.5	20.5–32.8	Southern Ocean

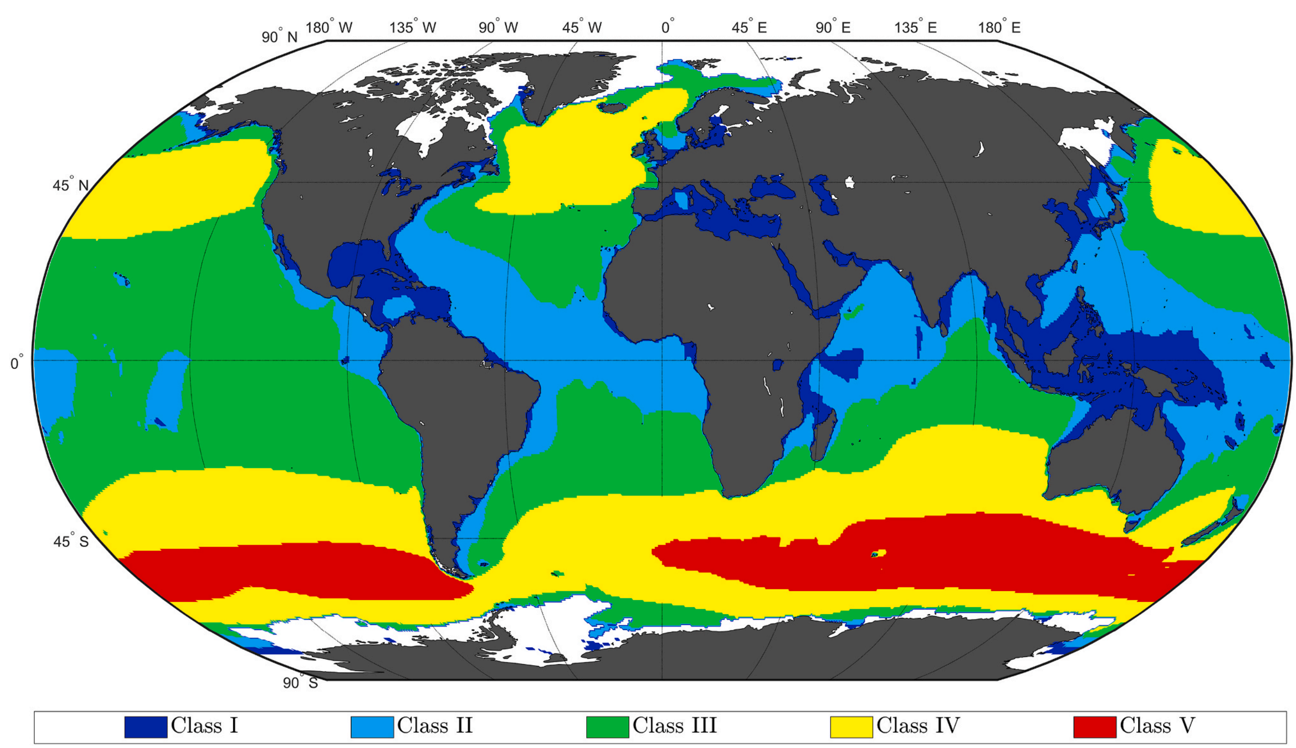

Fig. 5. Global distribution of the Wave Resource Classes (Table 1).

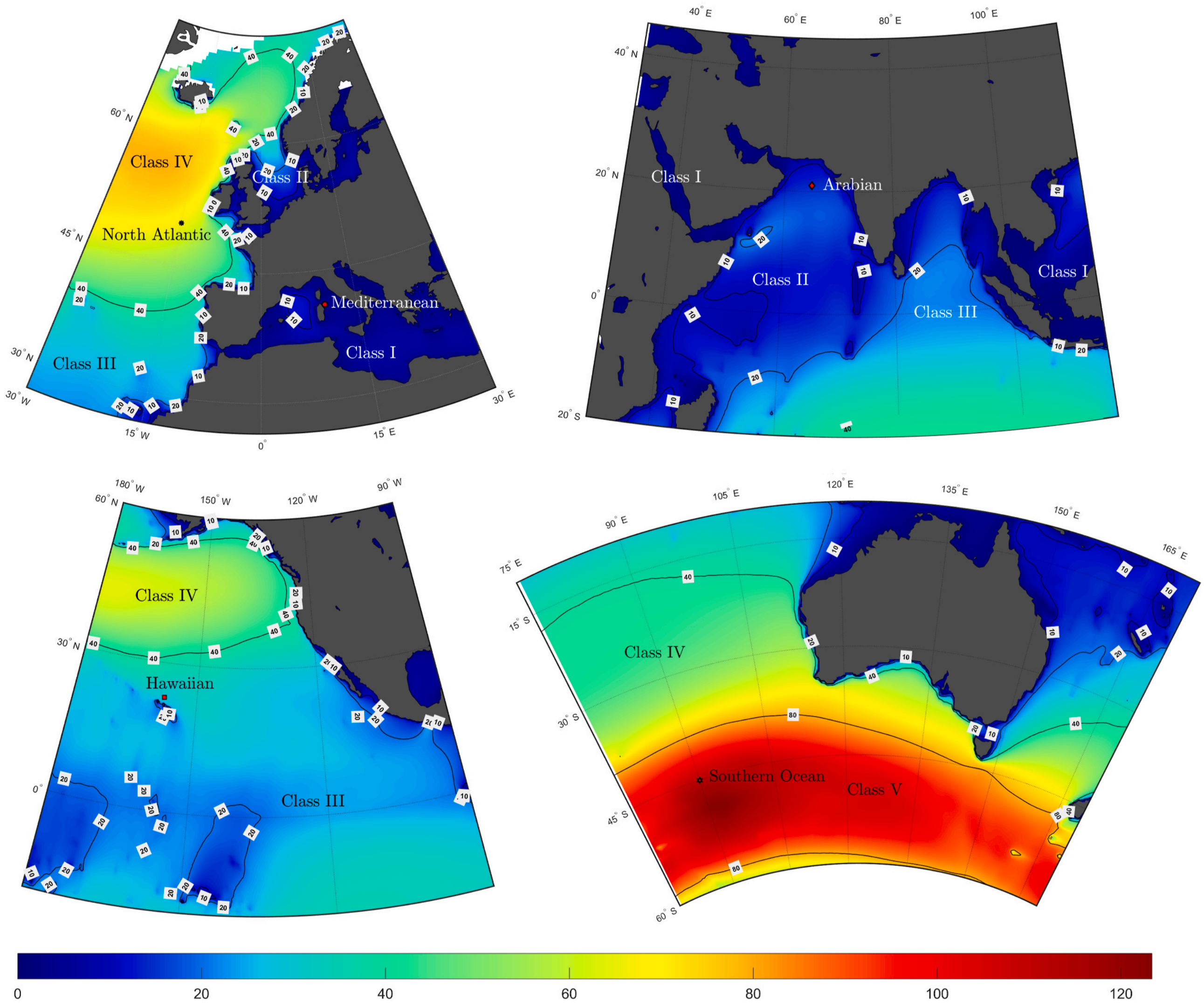

Fig. 6. Mean wave power (kWm^{-1}) and Wave Resource Classes in the regions from where they take their names. The representative sites are depicted by a black square.

80 kWm^{-1} (Table 1) and occurs exclusively in deep waters in the Southern Ocean – the oceanic belt north of Antarctica where the fetch is uninterrupted by land masses (Fig. 6d). Therefore, despite having the most energetic swells, Class V is of little practical interest.

4. Variability of the wave energy resource

In assessing the suitability of an area for wave energy exploitation the mean wave power, for all its interest, is not the only parameter that matters. The variability of wave power is also of great importance and, all else equal, areas with a high variability will in general be less attractive. Indeed, a high variability will impact the capacity factor of the WECs, the energy that will be produced during their service life and, therefore, the financial returns that the project will generate.

The coefficient of variation is obtained from the standard deviation σ and the mean value $\bar{x}$ of the statistical sample [46],

$$COV = \frac{\sigma}{\bar{x}}, \quad (9)$$

considering the entire database, spanning 40 years.

In the graph of the global distribution of the coefficient of variation (Fig. 7) three main trends are apparent. First, the wave power variability increases with latitude, all other things being equal; the lowest values occur in low-latitude areas (Tropical and Equatorial regions). Second, the Northern Hemisphere presents a greater variability overall than the Southern Hemisphere. Finally, the greatest variability occurs in semi-enclosed seas: Mediterranean Sea, Gulf of Mexico, Sea of Japan, etc.

Next, the global seasonal variability in a typical year is considered (Fig. 8). The year is divided into three-month periods: DJF (from December to February), MAM (from March to May), JJA (from June to August) and SON (from September to November). The seasonal variation presents two peaks of wave power, in the upper-middle latitudes of the Northern Hemisphere in DJF, with values over 140 kWm^{-1}, and in the upper latitudes in the Southern Hemisphere in JJA (the austral winter), with peaks over 150 kWm^{-1}.

The greatest seasonal variability occurs in the North Atlantic. Whereas the mean winter wave power values are well over 140 kWm^{-1}, the mean summer values do not exceed 35 kWm^{-1}. This substantial variability must be taken into account when planning the exploitation of the wave energy resource in the North Atlantic.

Generally speaking, the overall seasonal variability in the Northern Hemisphere is greater than in the Southern Hemisphere. For instance, the Pacific Ocean off central Chile has mean values of ~60 kWm^{-1} in winter and ~30 kWm^{-1} in summer.

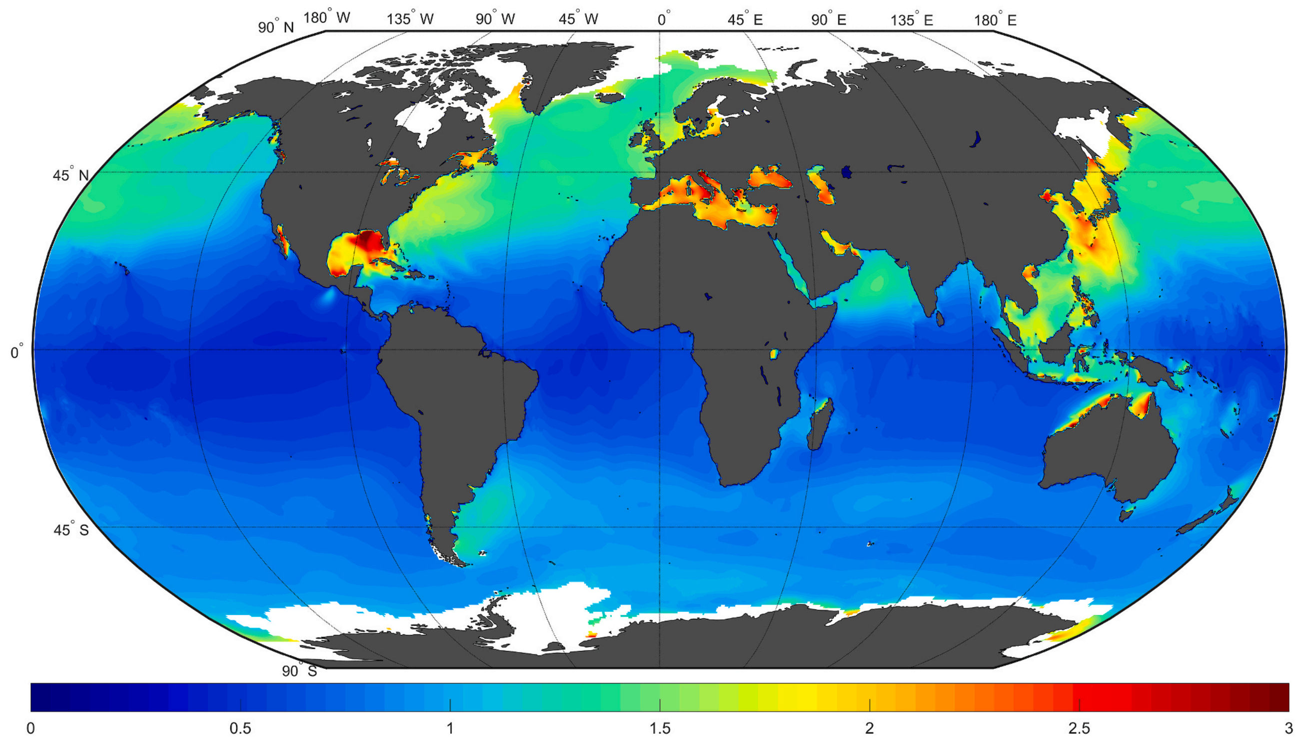

Fig. 7. Global distribution of the coefficient of variation (COV) of wave power.

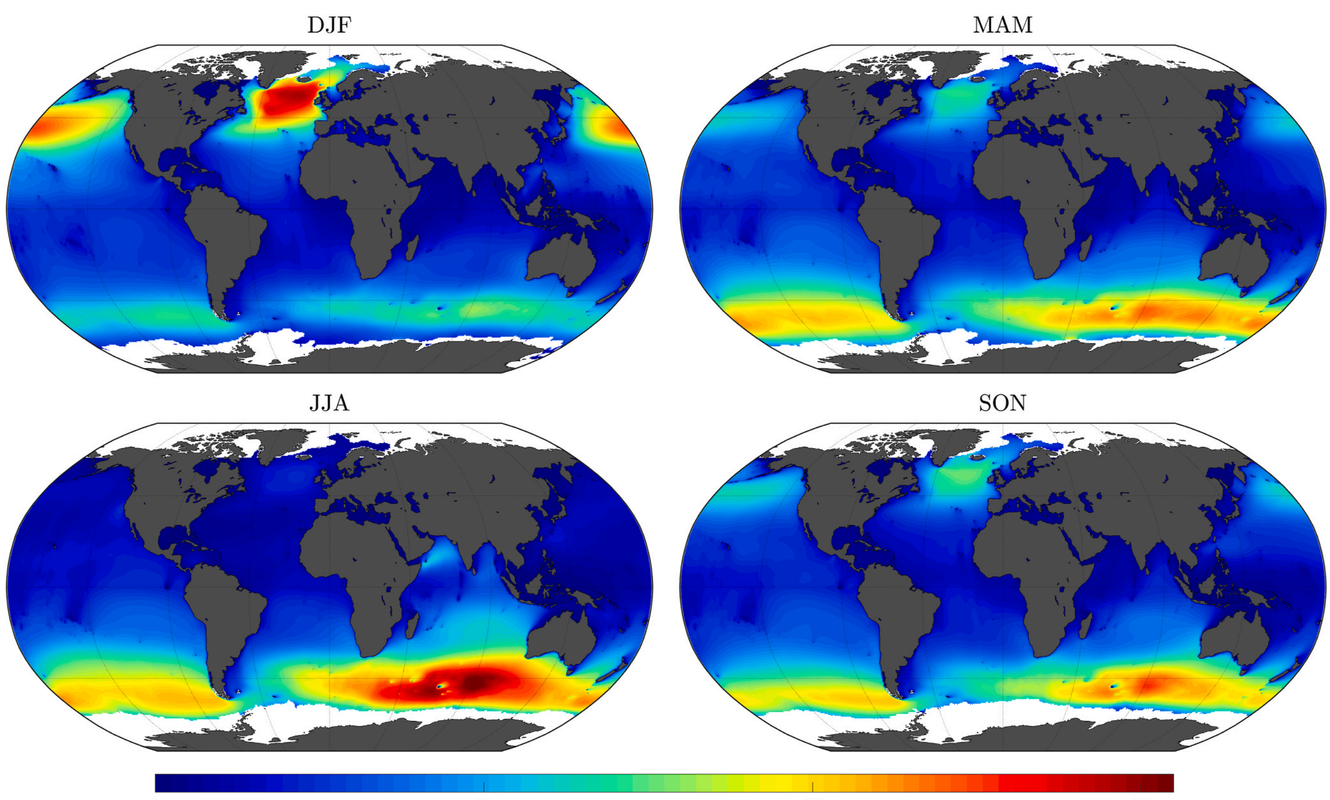

Fig. 8. Global distribution of mean seasonal wave power (kWm^{-1}): DJF- December, January and February; MAM - March, April and May; JJA - June, July and August; SON - September, October and November.

5. Wave exploitability index

The Wave Exploitability Index (*WEI*) is defined as

$$WEI = \frac{\overline{H_{rms}}}{H_{max}}, \tag{10}$$

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 period considered. The values in this work are obtained from the ERA-5 database spanning 40 years, from 1979 to 2019, as explained in Section 2.

The mean root-mean-square wave height in the numerator of the *WEI*, Eq. (10), corresponds to mean conditions, which are relevant in terms of wave farm operation and energy production. The maximum individual wave height in the denominator is representative of extreme metocean conditions, which determine the extreme loadings on the WECs and, indirectly, the costs of construction and maintenance. *Caeteris paribus*, the higher the *WEI*, the better the site for wave energy exploitation.

The purpose of this new index is to compare mean and extreme wave heights through a simple ratio, which can be readily evaluated over a large area using available metocean databases. Importantly, this comparison can be made prior to the selection of a particular WEC technology. The index is not aimed at incorporating values of energy generation by, or extreme loadings on, WECs, which would necessarily be specific to a particular WEC technology. These should be the object of a detailed investigation, once the WEC technology to be used has been decided.

Among other advantages, the *WEI* can be computed in a straightforward manner with easily accessible data. There are, of course, more complex approaches, which typically require additional data regarding the wave climate (frequency, persistence, etc.), the spectral characteristics of the resource, or even the ecological and social challenges posed by the WECs [47–49]. These complex approaches may be used, *inter alia*, to assess the loadings, and even the fatigue, that a WEC would experience at a particular site over its service life. For this reason they are appropriate for designing WEC structures or selecting a WEC for a particular site. The scope of the *WEI* is clearly different – it is appropriate for assessing the exploitability of the wave resource over a large area (even globally) at a low computational cost, prior to the selection of any particular WEC.

The global distribution of the Wave Exploitability Index is presented in Fig. 9, calculated as explained using Eq. (10) with 40 years' worth of global data. The highest values occur in the tropical and equatorial regions: Central and Northern South America (Colombia, Ecuador, Peru, Chile, Venezuela, Brazil), Western Central Africa (from the Gambia to Namibia), Indonesia (the West coast of Sumatra) and Southwestern Australia. It is interesting to see how regions such as Chile, mentioned before, present far better values than Western Europe, which on the basis of the mean wave power alone (Fig. 4) would be more attractive. The West coast of North America has also interesting values of *WEI*.

6. Discussion

In the conventional approach to the selection of areas for wave energy exploitation the emphasis is put on the mean wave power. For all its importance, this metric is not sufficient to characterise the wave resource.

The approach proposed in this work is based on two elements – a new classification of the resource and the novel Wave Exploitability Index (*WEI*). These two elements are combined in Fig. 10. Class I corresponds to low *WEI* values – little interest for wave energy exploitability. More importantly, the greatest *WEI* values do not correspond to the classes with the greatest values of mean power (IV and V) but to Classes II and III. This reflects the fact that it is not only the mean wave power that matters, but also the variability of the resource. Classes II and III occur chiefly in the lower and lower-middle latitudes in the Pacific, Atlantic and Indian Oceans (Fig. 10).

The scatter plot of the wave exploitability index (*WEI*) and mean wave power for all the grid points considered is presented in Fig. 11, along with the wave resource classes and their representative points. The pre-eminence in terms of wave energy exploitability of Classes II and III above Classes IV and V is apparent.

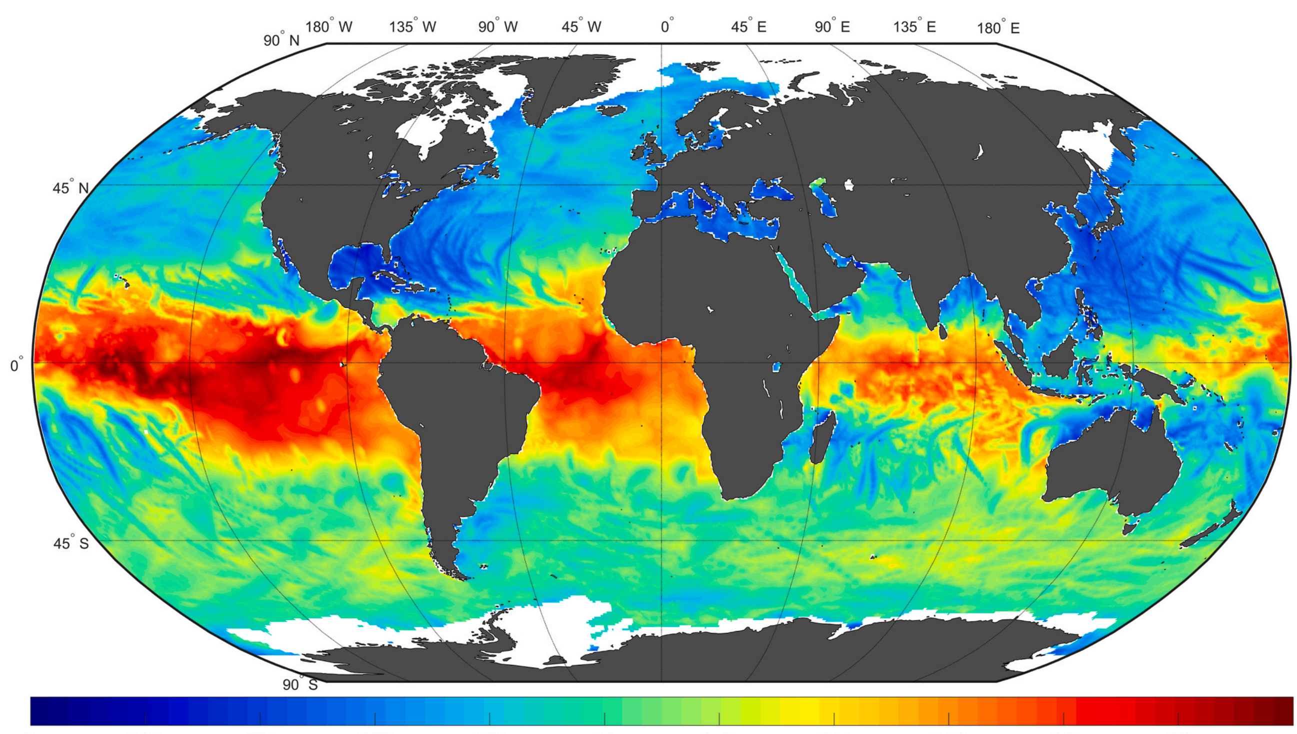

Fig. 9. Global distribution of the Wave Exploitability Index (WEI).

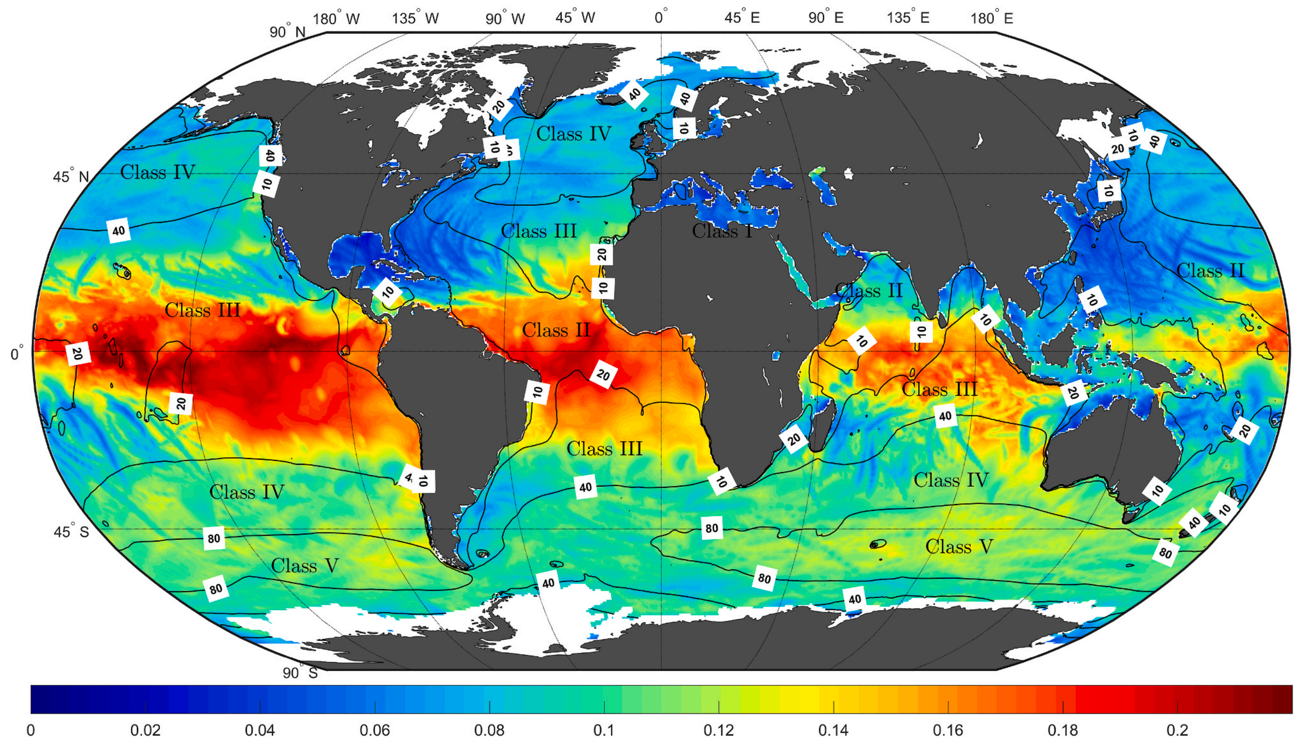

Fig. 10. Wave Exploitability Index (*WEI*) and wave resource classes in the global map, with the isolines of mean wave power (kWm^{-1}) that separate the classes. Colour scale: *WEI* values. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

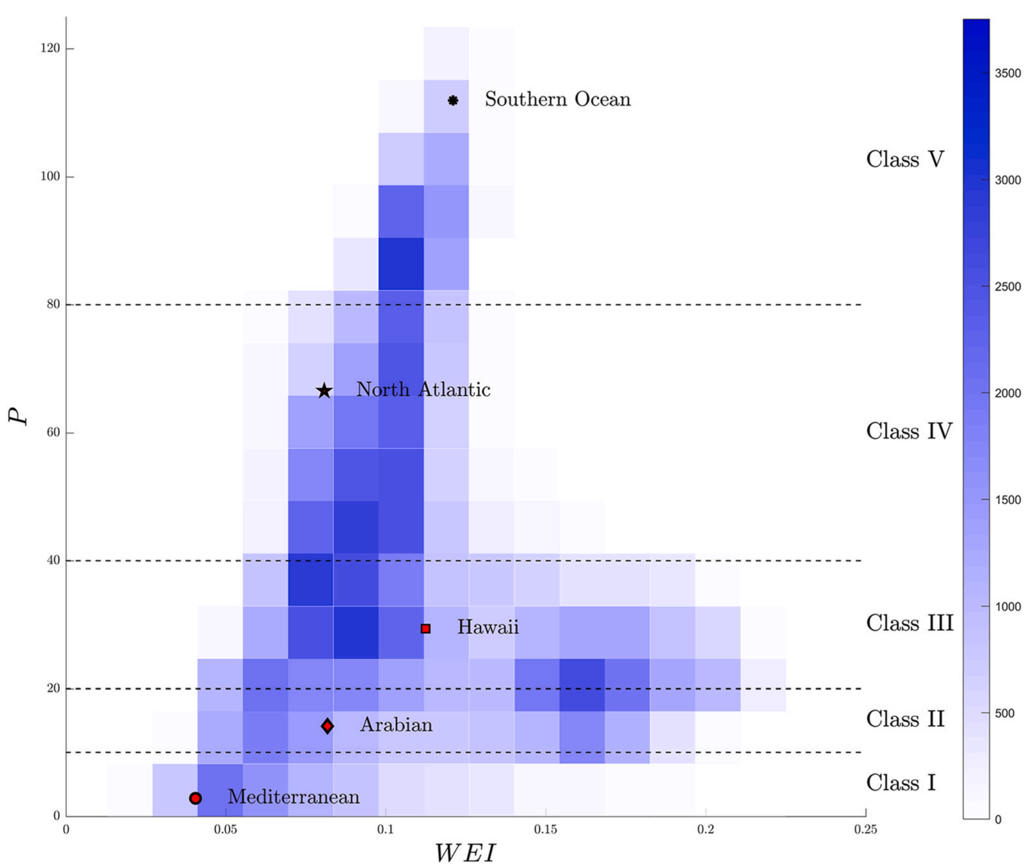

Fig. 11. Scatter plot of mean wave power (kWm^{-1}) vs. Wave Exploitability Index (*WEI*) encompassing all the grid points. The wave resource classes and their reference points are also depicted.

WEI values range from ~0.05 to ~0.20. An important aspect to note is that Classes II and III contain also a significant amount of points with low *WEI* values. It follows that the appraisal of the interest of a point, or otherwise, for wave energy exploitation should be based on the two approaches – the wave resource classification and the *WEI* index.

From the global variation of wave power (Fig. 3) and the wave resource classification (Fig. 5) it is clear that the mean wave power is determined, to a great extent, by latitude, with the upper-middle latitudes and, in particular in the Southern Hemisphere, upper latitudes possessing the greatest resource. This is due to two main factors: (i) the global atmospheric circulation and, more specifically, the westerlies prevailing in the mid-latitudes, which transfer a greater amount of energy to the ocean than the trade winds prevailing in the lower latitudes; and (ii) the scarcity of land masses in the upper latitudes of the Southern Hemisphere. Notable regions from the point of view of mean wave power are: Western Europe, Western North America, Southwestern South America and Southwestern Australia. These regions correspond to Class IV (Fig. 5).

Now, mean wave power on its own is not a good indicator of the interest of an area for wave energy exploitation. Many other factors come into play, some of which are unrelated to the wave resource itself and, therefore, outside the scope of this work, e.g., population density, energy consumption, electricity network capacity or competing uses of the marine space (fishing, aquaculture, recreation, nature reserves, military zones, shipping, etc.) There is, however, one other factor related directly to the resource: its variability.

It is interesting that the coefficient of variation (*COV*) of wave power is also greatly dependent on the latitude (Fig. 7), essentially increasing with it. Moreover, the Northern Hemisphere presents greater values overall, due to the large land masses and, consequently, the dynamics of counteracting oceanic and continental air masses (e.g., polar continental vs. polar maritime air). A similar difference between the Northern and Southern Hemispheres is apparent in the seasonal variability graphs (Fig. 8), with the Northern Hemisphere presenting far greater seasonal variability due to similar reasons.

This greater variability undeniably detracts from the interest of, e.g., Western Europe vis-à-vis the Southern Hemisphere areas with mean wave power values of interest, e.g., SW Australia or Chile. This is, of course, true as far as the resource alone is considered – more specifically, the mean wave power and coefficient of variation – without taking into account non-resource-related elements (population, energy consumption, electricity grid, etc.) Many of the latter would be more favourable in Western Europe and other regions of the Northern Hemisphere due to the higher population density.

The peak values of the *COV*, however, are located in enclosed and semi-enclosed seas, such as the Mediterranean and Black Seas, the Gulf of Mexico or the Sea of Japan, due to: (i) the interplay between continental and maritime air masses, which produces tropical and subtropical cyclones, also known as Medicanes in the Mediterranean; (ii) the complex topography of the enclosing land masses, which gives rise to, e.g., katabatic winds that generate large waves in small seas such as the Adriatic.

As for the Wave Exploitability Index (*WEI*), it is also highly dependent on the latitude, with the higher values occurring in the lower latitudes (Equatorial and Subtropical Regions) (Fig. 9) and lower values in the mid and upper latitudes. For a given latitude, the Southern Hemisphere generally presents a better *WEI* than its Northern counterpart, due to the reasons already explained (variability induced by land masses).

It is important to emphasise that enclosed and semi-enclosed seas have far lower *WEI* values than would correspond to their latitudes, as a result of the greater variability of the resource. Therefore, the Mediterranean, the Black Sea or the Gulf of Mexico are of very limited interest for wave energy exploitation.

7. Conclusions

A new approach for the selection of potential areas for wave energy harvesting was presented, based on two novel elements – a Wave Exploitability Index (*WEI*) and a wave resource classification.

The Wave Exploitability Index was introduced as a ratio of mean to extreme wave heights. It was defined on the basis of two variables which may be easily obtained from virtually any metocean database – the mean root-mean-square wave height and the maximum individual wave height. Other things equal, the higher the *WEI*, the better the site for wave energy exploitation.

The *WEI* enables ocean energy developers to carry out a first approximation to the areas of interest for wave energy exploitation using readily accessible data and at a low computational cost. Among other advantages, this means that large areas may be handled, as shown in the paper by considering the global resource.

The Wave Exploitability Index was found to be highly dependent on the latitude and Hemisphere (Northern vs. Southern). *WEI* values decrease generally with latitude and, for a given latitude, are generally larger in the Southern Hemisphere. An important caveat must be made in relation to this conclusion – enclosed and semi-enclosed seas (Mediterranean Sea, Black Sea, Gulf of Mexico, etc.) present consistently low *WEI* values irrespective of latitude. This is due to the fact that the greater the resource variability, the lower the *WEI* value.

The wave resource classification introduced distinguishes five Classes, from I to V, in order of ascending mean wave power. Each was named after an area of which it is typical: Mediterranean (Class I), Arabian (Class II), Hawaiian (Class III), North Atlantic (Class IV) and Southern Ocean (Class V). Using the most up-to-date database at the time of writing (ERA-5), spanning the period 1979–2019, the classes were mapped onto a global map.

The global distribution of the wave resource classes in the oceans (i.e., excepting enclosed and semi-enclosed seas) was found to be determined primarily by latitude. Thus, Classes II and III occur primarily in lower and lower-middle latitudes, and Classes IV and V in upper-middle and upper latitudes. As with the resource variability, the Northern vs. Southern Hemisphere dichotomy also plays a role, the greatest mean wave power values occurring in the Southern Hemisphere. In fact, Class V is specific to the Southern Ocean – an uninterrupted fetch that circumambulates the globe.

The exception to the control exerted by the latitude (and subsidiarily the Hemisphere) on the wave resource classes concerns enclosed and semi-enclosed seas, which belong essentially in Class I irrespective of latitude.

The areas that have so far attracted the most attention for wave energy development, in W Europe and the US West Coast, belong to Classes IV and V (mean wave power in excess of 40 kWm^{-1}) and are primarily in the Northern Hemisphere. At the other end of the spectrum, Class I, with mean wave power below 10 kWm^{-1}, is of little interest for wave energy exploitation for mass production. Wave energy for niche applications (maritime signals, oceanographic buoys, aquaculture, etc.) might still be of interest.

Finally, when the two elements proposed in this work, the Wave Exploitability Index and the wave resource classification, are combined, an important conclusion may be drawn – the areas with the highest *WEI* values do not occur in Classes IV and V, as might have been expected, but in Classes II and III (mean wave power between 20 and 40 kWm^{-1}). The combination of the highest values of the *WEI* and reasonably high mean power results in the emergence of new areas, such as SW Australia or Chile, which have so far received little attention. In this manner, it was shown that the new approach introduced in this work is a powerful tool for a first-order approximation to the areas of interest for wave energy exploitation at a global scale, which helps identify new potential areas for wave energy development.

Needless to say, for a more detailed selection of wave energy development sites this first-order approximation must be refined with additional information, e.g., distance to population centres, electricity demand, electricity grid, distance to adequate port infrastructure, marine reserves, shipping lanes, fishing areas.

Credit author statement

Abel Martinez: Conceptualization, Methodology, Investigation, Data curation, Writing – Original Draft Preparation. **Gregorio Iglesias**: Conceptualization, Methodology, Writing – Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The first author gratefully acknowledges the support of the Marine and Renewable Energy Centre Ireland (MAREI). This research was partially carried out in the framework of the project Intelligent Community Energy (ICE), INTERREG V FCE, European Commission (Contract No. 5025).

References

[1] Astariz S, Iglesias GJE. Enhancing wave energy competitiveness through co-located wind and wave energy farms. A review on the shadow effect 2015;8(7):7344–66.
[2] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. London, England: Sage Publications Sage UK; 2009.
[3] Abanades J, Greaves D, Iglesias G. Wave farm impact on beach modal state. Mar Geol 2015;361:126–35.
[4] Veigas M, Lopez M, Romillo P, Carballo R, Castro A, Iglesias G. A proposed wave farm on the Galician coast. Energy Convers Manag 2015;99:102–11.
[5] Astariz S, Perez-Collazo C, Abanades J, Iglesias G. Towards the optimal design of a co-located wind-wave farm. Energy 2015;84:15–24.
[6] Astariz S, Iglesias G. Selecting optimum locations for co-located wave and wind energy farms. Part I: the Co-Location Feasibility index. Energy Convers Manag 2016;122:589–98.
[7] Astariz S, Iglesias G. Selecting optimum locations for co-located wave and wind energy farms. Part II: a case study. Energy Convers Manag 2016;122:599–608.
[8] Carballo R, Sanchez M, Ramos V, Taveira-Pinto F, Iglesias G. A high resolution geospatial database for wave energy exploitation. Energy 2014;68:572–83.
[9] Carballo R, Sánchez M, Ramos V, Fraguela JA, Iglesias G. Intra-annual wave resource characterization for energy exploitation: a new decision-aid tool. Energy Convers Manag 2015;93:1–8.
[[10]] Khojasteh D, Khojasteh D, Kamali R, Beyene A, Iglesias G. Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy. Renew Sustain Energy Rev 2018;81:2992–3005.
[11] Contestabile P, Ferrante V, Vicinanza DJE. Wave energy resource along the coast of Santa Catarina (Brazil) 2015;8(12):14219–43.
[12] Iglesias G, López M, Carballo R, Castro A, Fraguela JA, Frigaard P. Wave energy potential in Galicia (NW Spain). Renew Energy 2009;34(11):2323–33.
[13] Rusu E, Soares CGJRE. Numerical modelling to estimate the spatial distribution of the wave energy in the Portuguese nearshore 2009;34(6):1501–16.
[14] Vicinanza D, Cappietti L, Ferrante V, Contestabile P. Estimation of the wave energy in the Italian offshore. J Coast Res 2011;(64):613.
[15] Vicinanza D, Contestabile P, Ferrante V. Wave energy potential in the north-west of Sardinia (Italy). Renew Energy 2013;50:506–21.
[16] Iglesias G, Carballo R. Wave energy potential along the death coast (Spain). Energy 2009;34(11):1963–75.
[17] Pontes MT. Assessing the European wave energy resource. 1998.
[18] Kamranzad B, Mori NJCD. Future wind and wave climate projections in the Indian Ocean based on a super-high-resolution MRI-AGCM3. 2S model projection 2019;53(3–4):2391–410.
[19] Carballo R, Sánchez M, Ramos V, Fraguela JA, Iglesias G. The intra-annual variability in the performance of wave energy converters: a comparative study in N Galicia (Spain). Energy 2015;82:138–46.
[20] Cornett AM. A global wave energy resource assessment. The eighteenth international offshore and polar engineering conference. International Society of Offshore and Polar Engineers; 2008.
[21] Mork G, Barstow S, Kabuth A, Pontes MT. Assessing the global wave energy potential. In: ASME 2010 29th International conference on ocean, offshore and arctic engineering. American Society of Mechanical Engineers Digital Collection; 2010.
[22] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304.
[23] Arinaga RA, Cheung KF. Atlas of global wave energy from 10 years of reanalysis and hindcast data. Renew Energy 2012;39(1):49–64.
[24] Reguero B, Losada I, Méndez F. A global wave power resource and its seasonal, interannual and long-term variability. Appl Energy 2015;148:366–80.
[25] Barstow S, Mørk G, Mollison D, Cruz J. The wave energy resource. Ocean wave energy. Springer; 2008. p. 93–132.
[26] Zheng C, Shao L, Shi W, Su Q, Lin G, Li X, Chen X. An assessment of global ocean wave energy resources over the last 45 a. Acta Oceanol Sin 2014;33(1):92–101.
[27] Pontes MT, Cavaleri L, Mollison D. Ocean waves: energy resource assessment. Mar Technol Soc J 2002;36(4):42–51.
[28] Mackay EBL. 8.03 - resource assessment for wave energy. In: Sayigh A, editor. Comprehensive renewable energy. Oxford: Elsevier; 2012. p. 11–77.
[29] Zheng CW, Wang Q, Li CY. An overview of medium-to long-term predictions of global wave energy resources. Renew Sustain Energy Rev 2017;79:1492–502.
[30] Reguero BG, Losada IJ, Méndez FJ. A recent increase in global wave power as a consequence of oceanic warming. Nat Commun 2019;10(1):205.
[31] Elliott, D., C. Holladay, W. Barchet, H. Foote, and W. Sandusky, *Wind energy resource atlas of the United States*. 1987, Pacific Northwest Lab., Richland, WA (USA).
[32] Hersbach H, Dee D. ERA5 reanalysis is in production. ECMWF Newslett. 2016;147(7):5–6.
[33] Portilla J, Sosa J, Cavaleri L. Wave energy resources: wave climate and exploitation. Renew Energy 2013;57:594–605.
[34] Lavidas G, Agarwal A, Venugopal V. Availability and accessibility for offshore operations in the Mediterranean Sea. J Waterw Port, Coast Ocean Eng 2018;144(6):05018006.
[35] Kamranzad B, Hadadpour S. A multi-criteria approach for selection of wave energy converter/location. Energy 2020:117924.
[36] López M, Iglesias G. Artificial intelligence for estimating infragravity energy in a harbour. Ocean Eng 2013;57:56–63.
[37] Greaves D, Iglesias G. Wave and tidal energy. John Wiley & Sons; 2018.
[38] Hasselmann D, Dunckel M, o Ewing JJJop. Directional wave spectra observed during. JONSWAP 1973;10(8):1264–80. 1980.
[39] Robertson B, Hiles C, Luczko E, Buckham B. Quantifying wave power and wave energy converter array production potential. Int J Mar Energy 2016;14:143–60.
[40] Connolly D. A user's guide to EnergyPLAN. Limerick, Ireland: University of Limerick; 2010.
[41] Carballo R, Sánchez M, Ramos V, Fraguela J, Iglesias G. Intra-annual wave resource characterization for energy exploitation: a new decision-aid tool. Energy Convers Manag 2015;93:1–8.
[42] Atan R, Goggins J, Nash SJE. A detailed assessment of the wave energy resource at the atlantic marine energy test site 2016;9(11):967.
[43] Lavidas G, Venugopal V, m e Friedrich DJIjo. Wave energy extraction in Scotland through an improved nearshore wave atlas 2017;17:64–83.
[44] Neill SP, Vögler A, Goward-Brown AJ, Baston S, Lewis MJ, Gillibrand PA, Waldman S, Woolf DKJRe. The wave and tidal resource of Scotland, vol. 114; 2017. p. 3–17.
[45] Iglesias G, Lopez M, Carballo R, Castro A, Fraguela JA, Frigaard P. Wave energy potential in Galicia (NW Spain). Renew Energy 2009;34(11):2323–33.
[46] Walpole RE, Myers RH, Myers SL, Ye K. Probability and statistics for engineers and scientists, vol. 5. New York: Macmillan; 1993.
[47] Felix A, Hernández-Fontes JV, Lithgow D, Mendoza E, Posada G, Ring M, Silva R. Wave energy in tropical regions: deployment challenges, environmental and social perspectives. J Mar Sci Eng 2019;7(7):219.
[48] Lavidas G. Selection index for Wave Energy Deployments (SIWED): a near-deterministic index for wave energy converters. Energy 2020;196:117131.
[49] Fairley I, Lewis M, Robertson B, Hemer M, Masters I, Horrillo-Caraballo J, Karunarathna H, Reeve DE. A classification system for global wave energy resources based on multivariate clustering. Appl Energy 2020;262:114515.