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REVIEW

Review of Wave Energy Resource Characterisation, Metrics, and Global Assessments

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Abstract

This paper provides an overview of the global wave resource for energy exploration. The most popular metrics and estimators for wave energy resource characterization have been compiled and classified by levels of energy exploration. A review of existing prospective wave energy resource assessments worldwide is also given, and those studies have been collated and classified by continent. Finally, information about forty existing open sea wave energy test sites worldwide and their characteristics is depicted and displayed on a newly created global map. It has been found that wave power density is still the most consensual metric used for wave energy resource assessment purposes among researchers. Nonetheless, to accomplish a comprehensive wave resource assessment for exploitation, the computation of other metrics at the practicable, technical, and socio-economic levels has also been performed at both spatial and temporal domains. Overall, regions in latitudes between 40° and 60° of both hemispheres are those where the highest wave power density is concentrated. Some areas where the most significant wave power density occurs are in offshore regions of southern Australia, New Zealand, South Africa, Chile, the British Isles, Iceland, and Greenland. However, Europe has been the continent where most research efforts have been done targeting wave energy characterisation for exploitation.

Keywords Marine energy; Wave resource assessment; Wave energy converter; Numerical wave models; Wave power density; WEC performance

1 Introduction

Ocean wave energy, because of its predictability and reliability, offers a promising opportunity to help reduce reliance on fossil fuels and support the transition to a more sustainable, diverse, and resilient energy mix. Moreover, the energy carried by ocean waves is dense and consistent compared with other renewable energy sources, and energy losses are small for long propagation distances.

Wave energy can be understood as a transformed form of solar energy. The differential heat gradient of the earth's surface promotes the generation of winds that, when blown over large widths of water, transfer part of the energy into waves. The magnitude of the energy transferred from the wind to the water surface (and hence the wave height and period) depends on the wind speed, the duration, and the distance over which it blows (fetch). The waves created locally close to the wind-blow generation area constitute the "wind sea" and exhibit a very irregular pattern. As these waves travel, they grow and progressively become regular and smoother waves characterized by greater wavelengths called "swell". As swell waves approach the shoreline travelling in waters of decreasing depth, the effect of the seabed, local currents, the geometry of the coastline, or shelter due to the presence of islands may provoke significant changes in wave direction and meaningful power losses.

Early attempts to convert wave energy date back a few hundred years, when France's first WEC patent was born in 1799 (Don Ross, 1995). Much later, Yoshio Masuda built the first floating oscillating water column attached to a navigation buoy in 1940 (Masuda, 1986). Since then, the

Article Highlights

- Globally, temperate regions of both hemispheres are those with higher wave power density, in offshore regions.
- Europe has been the continent where most research efforts have been done targeting wave energy characterisation for exploitation.
- Nowadays, numerical modelling is the most popular methodology for wave resource assessment.
- Existing research uses the available wave power density to compare the theoretical resource in different regions. However, other performance metrics at the practicable, technical, and socio-economic levels should be assessed.
- Despite the existence of several wave energy converter designs, no convergence yet exist towards the most efficient technology.

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geographical variability of wave patterns has resulted in various device types. Today, over a hundred different WEC concepts have been developed worldwide, with different maturity, working principles, directional alignment to waves, set-up locations, and PTO systems.

A review of the WECs deployed and demonstrated information about global technology developers, existing and forthcoming projects at open sea test sites is given in references (Magagna and Uihlein, 2015; Magagna et al., 2018; Ahamed et al., 2020; Bertram et al., 2020; OES-IEA, 2021; IEA-OES, 2023), and a library including photographic documentation of WEC concepts that reached the highest levels of development can be found in Tethys Engineering (2023). Details about the classification methods of WEC technologies are given in Guedes Soares et al. (2013), Bertram et al. (2020), and IRENA (2020). On the other hand, the most popular mechanisms for transforming wave energy into electrical energy and WEC control systems are given in Gallutia et al. (2022), Barua and Salauddin Rasel (2024). Most of the concepts are in the R&D stage, although some of them have reached full-scale prototypes and have been tested in the open sea. The most promising ideas for commercialisation include oscillating water columns (OWC), oscillating water surge converters (OWSC) and point absorbers (IRENA 2020).

Despite the wide range of WEC prototypes tested, convergence into commercial applications has not been reached yet, and the integration into the global energy market has been slow due to complex associated challenges, namely long-term survivability at sea, lack of consensus about the optimum design and PTO, lack of technological maturity, difficult storage, inland grid integration and high economic uncertainty (Kamranzad and Hadadpour 2020, Clemente et al., 2021). The LCOE of the wave energy (estimated at 0.27–0.54 €/kWh (IRENA 2021)) is still not competitive against that of other commercial renewables (0.027–0.11 €/kWh) (IRENA 2023) and fossil energy sources (0.045–0.16 €/kWh) (Our World in Data 2023). However, it is expected to stabilize and decrease as the learning curve progresses.

A detailed compilation of advantages and challenges that researchers and industry developers must overcome before large-scale wave energy conversion installations can be fully realized is given in (Gallutia et al., 2022). Nonetheless, despite its elevated cost, the exploitation of wave energy can still substantially increase energetic independence, especially in marine regions with high costs of imported energy, such as island territories. Some socioeconomic benefits linked to wave energy exploitation, among other MREs, are provided in (Bhuiyan et al., 2022). Furthermore, wave energy can efficiently supply flexible and low-cost power assurances for offshore projects with signi ficant power grid development requirements, such as marine farms, surveillance equipment, and drilling platforms (Chen et al., 2022).

Recently, the International Energy Association made efforts to set up common areas and parameters to evaluate the performance of wave energy exploitation (IEA-OES 2021). No international consensus has yet been reached on which metrics to use for a standardised evaluation of the wave energy resource at each of its exploitation levels. Thus, various diverse metrics have been estimated historically to characterize the wave resource and its potential at a given place or using a specific technology. The most popular ones have been compiled in (Guillou et al., 2020). However, a more exhaustive collection of the various parameters estimated in the literature is still missing.

This paper contributes to facilitating the understanding of wave energy evaluation parameters by providing a compilation and classification of the metrics most often estimated for the characterization of the wave resource at different levels of exploitation. Moreover, an overview of the global wave energy resource is given, and existing prospective wave resource assessments at different exploitation levels worldwide have been collated and classified by area of study. Finally, information about thirty-four existing worldwide wave energy test centres and their characteristics has been depicted and displayed into a newly created global wave test-sites map.

The paper is organised as follows: Section 2 classifies the estimators and metrics commonly used for wave energy assessment by exploitation levels. Section 3 presents an overview of global and continental wave energy resource assessment studies. Section 4 compiles details about existing wave energy test sites around the world. Finally, Section 5 includes the main conclusions retrieved from this review.

2 Estimators and metrics for wave resource characterisation

Different levels characterize the wave energy conversion process using WECs, from the net available resource to delivering power to the grid to reach the final user (Figure 1), somehow inspired by the classification used in previous references (ESBI, 2005; ABP MER, 2008; Dalton et al., 2010; Mørk et al., 2010). This review classifies the resource levels as theoretical, practicable, technical, and socio-economic.

Level 1, referred to as *theoretical potential*, is related to the raw wave resource available and its climate. Wave climate, extreme analysis, and energy resource statistics are commonly performed to assess the resources at this level. The met-ocean metrics associated with this level have also been referred to as pre-production metrics (Guillou et al., 2020) and include the significant wave height, peak and energy periods, mean direction, the available power density, the long-term statistics of those parameters or bivariate scatter diagrams, among others.

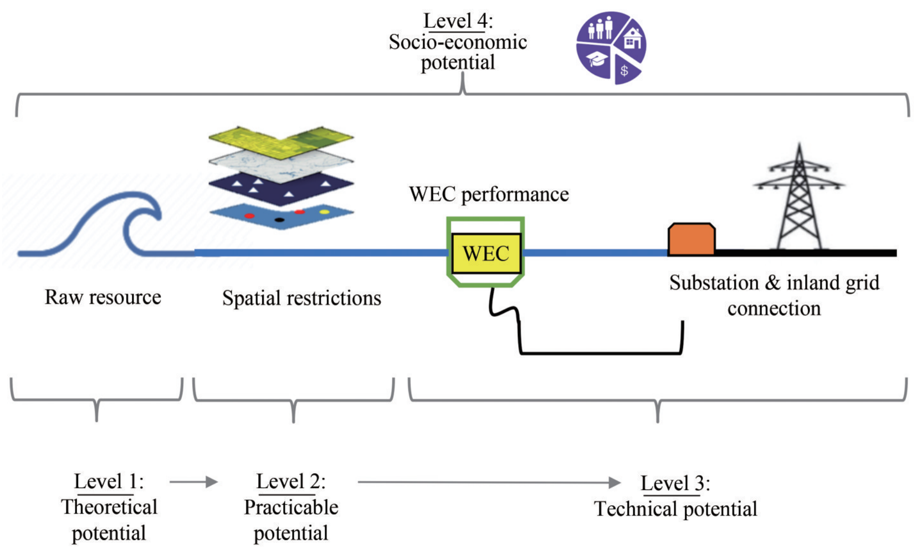


Figure 1 Levels characterizing the wave energy conversion process, from the net available resource to delivering power to the grid

Level 2, referred to here as *practicable potential*, accounts for the energy potential of the areas where its extraction is feasible and accessible. Its assessment includes rejecting areas constrained due to impracticable water depths or distances to shore, environmental or safety constraints, other marine uses and existing activities, or other spatial criteria that would make deploying a wave farm inappropriate. Evaluating the resource at this level requires marine spatial planning metrics and techniques.

Level 3, referred to as *technical potential*, is related to the WEC performance and the transmission system of the energy to shore. Not all WEC technologies are equally appropriate for every wave environment. The extent to which a WEC can convert the locally available power into output power is given by its power matrix ($PM_{i,j}$) and rated power (*Rp*), which depend on the symphony between the sea state and the WEC's dimensions, working principle and PTO. Generally, device developers provide their power matrixes in terms of power output (kW) or efficiency (%) for the different sea states. The most popular metric to characterise the resource at this stage is the Power Output (Po), which measures the energy the WEC can capture and convert given a specific sea state. If the WEC power rating is too high to a magnitude that is rarely available, it will end in significant investment costs in relation to the generated electricity. The wave power output increases with the available power and when its variability is lower. The power transferred from the WEC to the onshore grid for energy consumption is represented by the Delivered Power (P_d). The transport of the ocean power to the onshore grid is usually done through array and subsea electrical systems, substations, and a submarine cable connection to the shore in a process associated with energetic and economic challenges. The energy loss coefficient (η_{loss}) accommodates transmission losses, wake effects, downtime losses due to maintenance, and technical failures. It has been estimated that these losses can range between 6% to 10% of the power outputting the WEC (Henfridsson et al., 2007). Metrics used in the literature to characterize the wave resource at this technical level have also been referred to as "post-production metrics" (Guillou et al., 2020).

Level 4, or *socio-economic potential*, goes beyond pure energy potential and considers other social, economic, and environmental criteria influencing the return of a wave farm. Social impacts address various issues ranging from well-being and quality of life to employment and local income. Economic criteria include, for example, water depth and remoteness, which can highly impact life cycle costs by affecting the installation and maintenance cost of a wave energy exploration facility. Environmental criteria address potential impacts associated with a project's activities (manufacture, installation, O&M and decommission) and can be evaluated through techniques such as the Life-Cycle Assessment. Various studies have proposed indicators, including socio-economic criteria, to support the decision-making process, seeking to determine the optimal location to minimize the environmental impact and maximize the socio-economic return. However, it is important to highlight that several uncertainties are still linked to quantifying social and economic parameters of wave energy generation due to the lack of demonstration technologies and real data. Uihlein & Magagna (2016) gave a good classification and review of different criteria at the practicable and socio-economic levels to be considered when performing a complete resource assessment for exploitation.

Various metrics, depicted in Table 1, have been used in the literature to characterise the wave energy resource at each of these levels. A detailed description and reference for each of these metrics are further included in Supplementary Material 1. Although output metrics were often found to be referred to differently in different publications, the same nomenclature has been used to classify them in this review as homogeneously as possible. As inputs to those metrics, raw wave resource parameters able to describe the sea state conditions and its variations in the local of interest are needed (such as the wave spectra or the integrated values of the significant wave height and periods). Historically, different data sources have been exploited, and diverse approaches have been followed to retrieve those intrinsic wave parameters, such as observation and measurements, physics-based numerical simulation, and statistic-based analytical models. An extended overview of those methods can be found in (Ramos-Marin and Guedes Soares, 2024).

Conversely to the main trend (which evaluate wave resource metrics in terms of historical wave conditions), some studies have evaluated the wave resource metrics for the near future by projecting the expected wave parameters in different climate-change scenarios, which better represent the conditions that those devices will encounter when put into operation (Ribeiro et el., 2020, Simonetti and Cappietti 2023).

3 Review on wave energy characterization studies

Existing prospective global and regional assessments of the wave energy resource up to date have been collated. Details about the methodologies used, input data, simulation period, analysed resource level, output metrics and spatial and temporal resolution have been included in this review.

3.1 Global wave resource characterization

One of the first assessments of the global wave energy resource was presented by Kinsman (1965). Based on experimental observations and openly admitted not rigorous guesses, he estimated the global power potential to be around 2 TW, which is still the most popular value in the literature (Reguero et al., 2015). Between 1973 and 2000, several authors performed improved global wave power assessments and came up with values ranging from 0.8 to 3 TW (Inman and Brush, 1973; Isaacs and Seymour, 1973; Panicker, 1976; Quayle and Changery, 1981; Hogben and Dacunha, 1986; World Energy Council, 1993; Pontes, et al., 1998; Krogstad and Barstow, 1999). Most of these global wave energy studies estimated the available power based on visual observations, satellite data, simplified formulations or first and second-generation numerical models and suggested potential locations for energy extraction based on the energy hotspots. From the early 2000 s up to date, most of the research on global resource assessment was based on reanalysis data products outcoming from existing deep and shallow water third-generation simulation models, often validated against available in-situ or remote observations (Ahn et al., 2022; Arinaga & Cheung, 2012; Barstow et al., 2003, 2009; Caires et al., 2004; Caires & Sterl, 2005; Chawla et al., 2013; Chen et al., 2013; Cornett, 2009; Folley et al., 2012; Gunn & Stock-Williams, 2012; Lavidas & Kamranzad, 2021; Law-Chune et al., 2021; Martinez & Iglesias, 2020; Mørk et al., 2010; Reguero et al., 2011, 2015; Ringwood & Brandle, 2015; Rusu & Rusu, 2021; Sasaki, 2017; Sterl & Caires, 2005; Stopa et al., 2013). Results from Gunn and Stock-Williams (2012) estimated that out of the total wave power incident on the ocean-facing coastlines worldwide (≈2.11 TW), the effective extractable power could be about 97 GW considering a state-of-the-art WEC, representing an efficiency of approximately 4.6%. Table S2.1 (Supplementary Material 2) shows detailed specifications of existing global wave energy assessments.

Generally, the main objective of existing research has been to assess the theoretical wave energy potential in terms of traditional parameters, such as average annual significant wave height (*Hs*), energy period (*Te*), mean direction (θ_m), and wave power density (*Pw*). Moreover, there has been a particular focus on generating longer and higher resolution models by hindcasting ocean and atmospheric models or downscaling the updated available data (Sterl et al., 1998; Reguero et al., 2012; Hemer et al., 2013; Rascle and Ardhuin, 2013; Alday et al., 2021).

An idea of the global distribution of *Hs*, *Tp* and *Pw*, resulting from one of the latest worldwide assessments (Kamranzad et al., 2022) is given in Figure 2.

Resource variability has often been evaluated to assess the effects of climate change (Morim et al., 2019). The CoV has been one of the most used metrics to evaluate resource variability. Figure 3 compares the global results of this parameter as given in (Martinez and Iglesias, 2020; Rusu and Rusu, 2021).

For the assessment of the future viability of marine energy projects, the extreme events have often been evaluated as

Table 1 Most common metrics and indexes used for wave energy resource assessment (A description, units and references for these metrics are described in Supplementary Material 1)

Level 1: Theoretical potential	Level 2: Practicable potential	Level 3: Technical potential	Level 4: Socio-Economic potential
$S(f, \theta)$, m_n, *Hs*, *Tp*, *Te*, *Tm*, *Ts*, f_p, w_p, f_m, w_m, w_z, θ_m, θ_p, $S(f)$, $\sigma_\theta(f)$, OP_{ht}, *Ew*, *Pw*, Pw_n, *Pe*, FP, FDP, Stats, *Rr*, CoV, AVI, SVI, MVI, RoC, WEDI, WDW, t_i, OHI, SIp, WEI, Ac_f, Qp	SG, WD, DS, DP, D_{sub}, Uw_c, Env_c, CT, OU	*Po*, *Eo*, *Cw*, Cw_R, *Cf*, P_d, *U*, *Af*, *Uf*, S_{th}, SIWED, MCA, EROI, EPBT	LCOE, NPV, IRR, LCA, SCOE, S_s, I^k

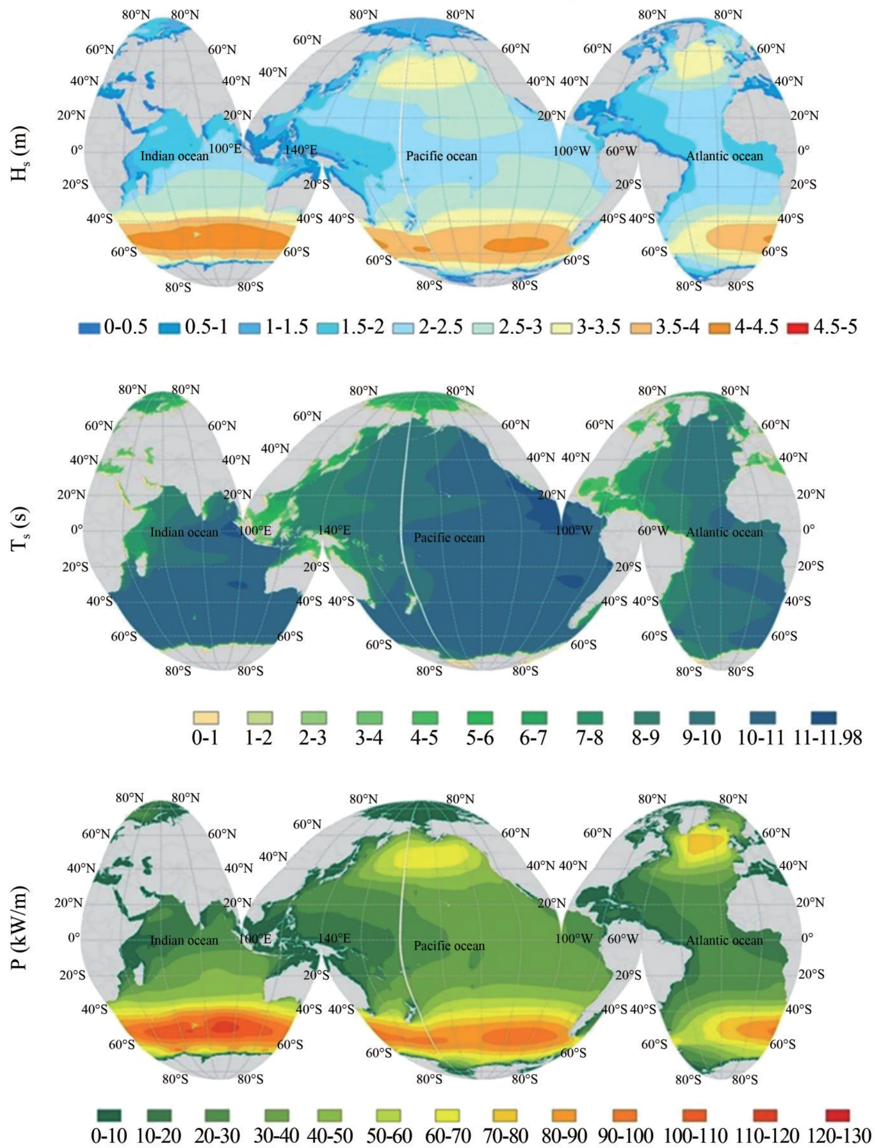
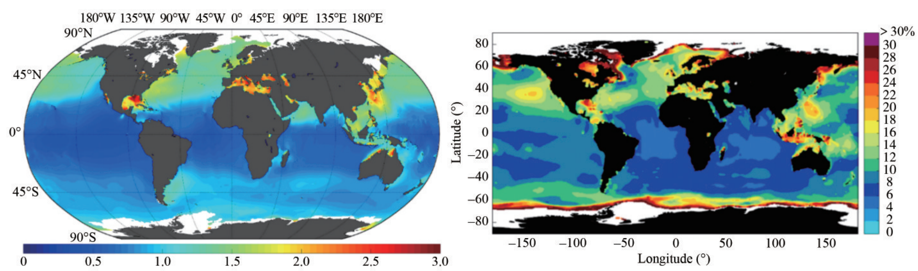


Figure 2 Significant wave height (*Hs*), energy period (*Te*) and power density (*Pw*) estimations from one of the most recent global wave resource assessments (Kamranzad et al., 2022)



(a) Global CoV distribution by (Martinez and Iglesias 2020)

(b) Global CoV distribution by (Rusu and Rusu 2021)

Figure 3 Global CoV distribution from most recent global resource assessments

well through metrics such as exceedance probabilities, extreme wave heights for a determined return period of years (H_5, H_{50}, H_{100}), and Relative Risk ratios (*Rr*) (Bhaskaran et al., 2023; Neary and Ahn, 2023).

Besides the traditional parameters, several authors proposed the estimation of other less popular or novel metrics to assess the adequacy of the wave resource for exploitation. Examples are Goda's peakedness parameter (Qp), a risk parameter, and the wave directional width (WDW), given in Fairley et al. (2020); the Wave Exploitability Index

(WEI) given in Martinez and Iglesias (2020); the Wave Energy Development Index (WEDI), and rate of change (RC), given in Lavidas and Kamranzad (2021); and the frequency-constrained wave power (FP) and the frequency-directionally constrained wave power (FDP) proposed in Ahn et al. (2022).

Using one or a combination of single parameters, Fairley et al. (2020), Martinez and Iglesias (2020) and Ahn et al. (2022) developed a classification system to split the global wave resource into different suitability classes for wave energy exploitation. With the same purpose, Farley et al. (2020) used a K-means clustering method using two sets of input data: a simple set (based on *Hs* and *Tp*) and a comprehensive set including a wide range of other relevant wave climate parameters (*Qp*, extreme events, risk parameter, WDW); Martinez & Iglesias (2020) based their classification on the mean wave power; while Ahn et al. (2022) consider the combination the total wave power density, the FP and the FDP. Kamranzad et al. (2022) re-defined the suitability of global hotspots for wave energy extraction. They are represented by employing the Sustainability Index (SIp), which defines the suitability of the sea conditions for wave farm deployments by relating the mean annual power density, the long-term rate of change, and the variation in the monthly variability index. Figure 4 provides the global suitability distribution for the exploitation of wave energy. Higher values represent better conditions.

Although slight differences in wave power estimations exist in publications due to the use of different simulation methods and input data sets, an almost consensual distribution of the overall wave power resource has been observed. The highest wave energy resource is found to be concentrated in latitudes between 40° and 60° in both hemispheres. Thus, latitude is one main factor affecting the spatial variability of the wave power resource (Guo and Ringwood, 2021).

The South Hemisphere is characterized by higher mean annual wave power than the North Hemisphere due to higher seasonal variations and larger continental masses in the latter (which provokes the development of shorter fetches) (Martinez and Iglesias, 2020). Figure 2 shows that the areas with the most significant wave power density are in the temperate zone of the South Hemisphere and cover the offshore regions of southern Australia, New Zealand, South Africa, and Chile. The maximum simulated values occurred in the Southern Indian Ocean, between the Kerguelen Island and the southern coasts of Australia, where *Hs* rounds 4.5–5 m, *Te* exceeds 9 s and *Pw* rises over 120 kW/m. The lowest energy resource in this hemisphere is found between the Northern Coast of Australia and southern Indonesia and Papua New Guinea, where the mean power density does not exceed 5 kW/m (Rusu and Rusu, 2021). In most areas of this hemisphere (Southern coasts of Australia, Tasmania, New Zealand and Chile), the predominant contributor to the mean annual wave power density is the primary swell, while in regions such as southern South Africa, the wind waves have a more substantial impact (Arinaga and Cheung, 2012). Regarding the Antarctic continent, even though wave power is a possible energy source for the coastal stations in the future (Mckenzie et al., 2010), there has been barely any interest in evaluating its potential for exploitation due to the great ice-covered extent of the surrounding ocean, and the technical limitations of current exploitation technologies (West et al., 2016).

In the Northern Hemisphere, the highest wave height power density values are found in the North-Atlantic zone, offshore the British Isles, Iceland, and Greenland coasts. Up to 4 m and 90 kW/m of Hs and Pw have been estimated near the Azores archipelago, respectively (Lavidas and Kamranzad, 2021). However, up in the Arctic waters, the substantial diminishing of sea ice has been found to induce local and regional changes in both mean and extreme wave conditions (Christakos et al. 2024). Interestingly, the European Northeast Atlantic region stands out in relation to the Pacific because of the two centres of action that govern the atmospheric circulation in this region: the Iceland Low and the Azores High (Martinez and Iglesias 2020). The Pacific waters surrounding the west coast of Canada, Washington and Oregon also have significant values of Hs (apx. 3 m), Te (apx. 9 s) and wave energy (ranging from 20 to 60 kW/m as latitude increases). Lower levels of Hs and wave power (apx. 2 m and 15–20 kW/m) are found in the Pacific equatorial waters (see Figure 2), with the highest energetic potential in Northern Peru and Ecuador. In the Equatorial waters, mean energy periods reach up to 10 seconds, indicating that some swell waves propagate eastwards through the Pacific and reach the equatorial coasts. The Western Pacific side, covering the coast of Japan and the Russian Bering Sea, is characterized by the highest power resource in the Asian Pacific (with average power values of 20–40 kW/m). Smaller annual mean values are found at the surrounding waters of south-eastern China, north-eastern Indonesia, and the Philippines (average power densities of 2–20 kW/m) (Martinez and Iglesias 2020, Rusu and Rusu 2021).

The lowest global values were estimated in the enclosed or semi-enclosed basins (Black Sea, Mediterranean Sea, Baltic Sea, Red Sea, Persian Gulf, etc.), with average power density values rounding between 2 and 13 kW/m (Bozzi et al., 2018, Guillou et al., 2020b), or in sheltered coastal regions like the Gulf of Mexico (mean $Pw \leqslant 13$ kW/m (Guillou and Chapalain 2020)), the Caribbean Sea (mean $Pw < 8$ kW/m (Guillou and Chapalain 2020)), or the Indonesian inner seas (mean 6 kW/m (Ribal et al., 2020)).

Resource assessments in island territories received special attention due to their isolated nature and their need for energy independence and sustainable development (Rusu and Onea 2019, Ramos et al., 2020). The minimum wave

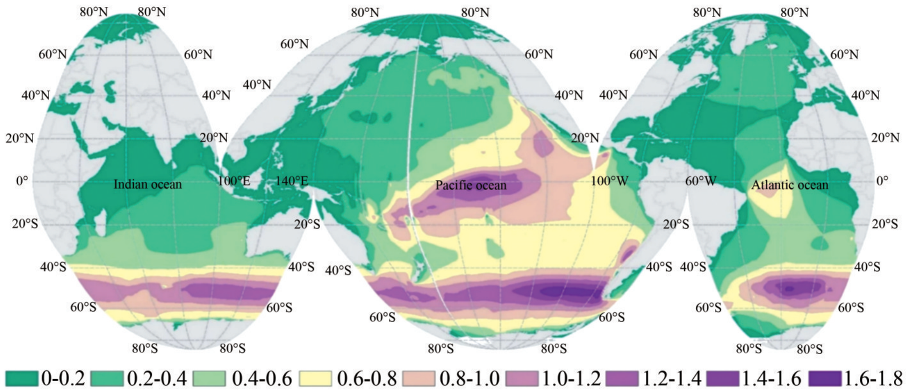


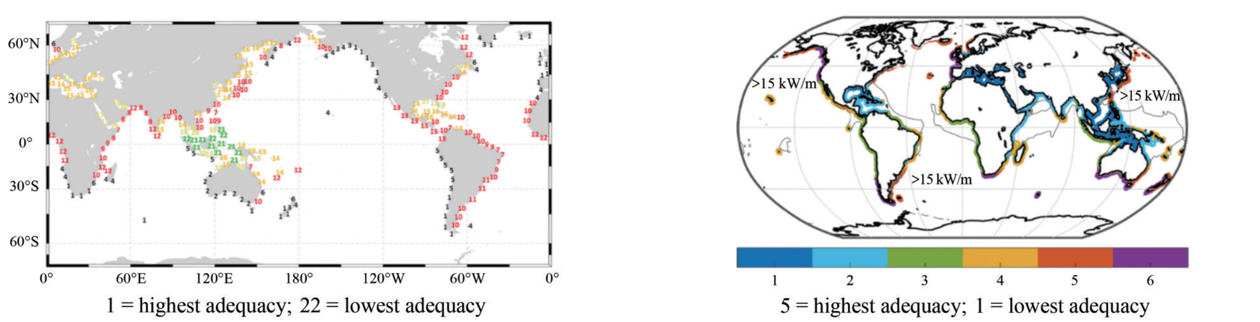
Figure 4 Sustainability Index (SIp) estimations from the most recent global wave resource assessment (Kamranzad et al., 2022)

power value among global islands (2.28 kW/m) was estimated close to the island of Sulawesi (Indonesia), compared to a maximum of 68.8 kW/m encountered close to Tasmania (Australia) (Rusu and Onea 2019).

However, some areas characterized by significant power density levels, such as the Western Coasts of Europe, are also characterized by the most significant seasonal wave power variability. This phenomenon makes other regions with lower mean power density, such as the coast of Chile, more reliable for exploitation when considering variability factors (Martinez and Iglesias 2020). Temporal variability is lower around the Equator in the Atlantic, Pacific and Indian Oceans, except for the Arabian Sea, the Bay of Bengal and northern Australia, Indonesia, Malaysia, and the Philippines (Cornett 2009). The highest variability occurs at greater latitudes of both hemispheres, in seasonally ice-covered sites, such as the Beaufort Sea, Sea of Okhotsk, the northern Bering Sea and the waters around Greenland and Australia. However, influenced by the "El-Niño" phenomena, the resource is also unsteady in Central America, the Gulf of Mexico, and the Caribbean Sea (López et al., 2013).

Although offshore regions are more energetic overall than nearshore areas (due to the increase in wave energy dissipation shoreward), offshore locations are often improper for any wave energy project because of the unfeasible considerable distance to shore and small survivability chances. Under the current state of the art, the mean depth of wave energy exploitation using WECs is around 50–60 m (Barstow et al., 2008). Results of the adequacy ranking for wave energy exploitation by Farley et al. and Ahn et al. (Fairley et al., 2020, Ahn et al., 2022) are shown in Figure 5. Figure 5a represents a scale of increasing adequacy from 1 to 22, meaning that locations assigned with one present the highest interest for the wave energy exploitation, and those attributed with 22 the lowest. Figure 5b is given on a scale of 5 classes that decrease in adequacy (class 5 for highest adequacy and class 1 for lowest). The results presented by both authors mostly agree, indicating that the locations with the highest potential for wave energy exploitation, in terms of combined parameters, are those located on the coast of South Africa, Chile, Western Europe, Southern New Zeeland, West and South Australia, West of Canada, and the Gulf of Alaska. Conversely, the coasts showing the lowest potential are those in the Indonesian, Asian and Arabian enclosed seas and gulfs, such as the Arafura Sea, the Gulf of Bothnia, the Persian Gulf or the Yellow Sea. Moderate conditions (scores between 4 – 5 in (Ahn et al., 2022) and between 10–12 in (Fairley et al., 2020)) have been attributed to coastal areas of Brazil, Argentina, Uruguay, Eastern USA, Northern and Eastern Africa, China, and Japan.

Besides the published papers and reports, recently some entities have built up online platforms where wave climate



(a) Global adequacy for wave energy exploitation by Ahn *et al.* (2022)

(b) Global adequacy for wave energy exploitation Fairley *et al.* (2020)

Figure 5 Adequacy ranking for wave energy exploitation by different authors and wave power information can be interactively visualized in a map format and downloaded for different global regions (among other related spatial features). Examples include the Copernicus global database platform (Copernicus Global Database 2022); Marine Energy Atlas by NREL, where wave power and climate data models can be visualized for the United States (NREL 2022); the Australian Marine Energy Atlas, by CSIRO and the Australian Government (Australian Marine Energy Atlas 2022, CSIRO 2022); and the MORE-EST platform which includes data for the European continent (including the Mediterranean and Black Sea) by the University di Torino (MORE-EST 2022).

3.2 Wave resource characterization by continents

An overview of the wave energy resource in the different continents has been synthesized after reviewing over a hundred scientific papers. The highest number of publications reviewed were found to assess the resource in European waters (35%), followed by Asia (25%), North America (12%), South America and Oceania (9%) and Africa (7%), as per Figure 6. Further details about the reviewed publications by continents are given in Tables S2.2 to S2.8 (see Supplementary Material 2).

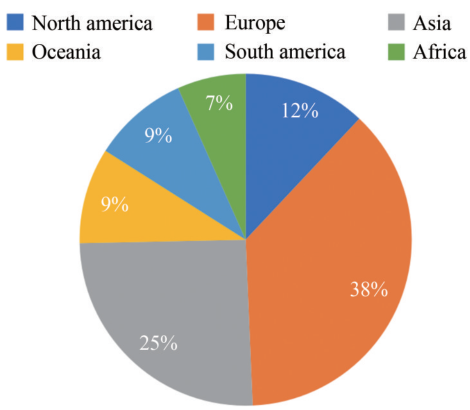


Figure 6 Regional focus of reviewed publications dedicated to wave energy resource assessments

3.2.1 North America

In terms of theoretical resources, the most significant wave energy potential in North America is found along the Pacific Northwest Coast of the USA, Canada and the southern coast of Alaska (exceeding 46 kW/m, or 400 MWh/m). Waters along the coast of California and Hawaii have moderate energy compared to those along the Pacific Northwest Coast, on the order of 34 kW/m (300 MWh/m). Southern on the Pacific, the average wave power along the American Samoa's coastal waters was estimated about is 14 kW/m (Garcia-Medina et al., 2023). The waters along the East Coast and Atlantic Ocean side of Puerto Rico are typically below (power densities below 26 kW/m and energy density about 100 MWh/m). The lowest energy, excluding arctic Alaska, occurs in waters in the Gulf of Mexico and along the Caribbean waters of Puerto Rico (average power densities below 10 kW/m and 50 MWh/m) (Robertson et al., 2016; Ahn et al., 2019, 2020). Nonetheless, some studies show that energy harvesting in the Mexican Caribbean is still feasible, especially in the northern coastal area of Cancun, where the power availability averages 45.6 MWh/m/yr (Chávez et al., 2023).

Regarding the temporal variability of the resource, the largest inter-annual oscillations occur within the Bering Sea below the Alaskan Arctic region and the central-eastern Gulf of Mexico. On the other hand, the seasonal variability is highest in the nearshore arctic areas because of the effects of intermittent ice cover. Following this, the Pacific Northwest Coast, the southern coast of Alaska, and the northern coast of Hawaii also present significant seasonal variation. Along the Florida Shelters, the eastern Gulf of Mexico also presents a large variability where the most energetic seas are primarily concentrated in winter. Conversely, the seasonal variation is low in the coastal waters along California. Therefore, despite the Pacific Northwest being a more considerable power resource, coastal California may offer better opportunities with a more reliable and steady energy supply (Ahn et al., 2020).

To provide technical information for technology designers, Ahn et al. (Ahn et al., 2019) created a classification system that involves key resource attributes relevant to the design and operation of a WEC (such as the matching between the most energetic wave period bands of a location with the operating resonant period bandwidth of a WEC technology). According to this classification, the most energetic regions that support utility-scale applications are predominant all along the West Coast, the northern and eastern shores of Hawaii, the southern coast of Alaska extending west along the Aleutians, and offshore locations in the Bering Sea. Second in the classification scale, sites were spotted along the East Coast and the southern portion of the West Coast. Sites attributed with lower classification were found along the Gulf Coast and along the west coast of Alaska and offshore in the Bering Sea above sixty-degrees latitude (Ahn et al., 2019).

On practice, just a few prototypes of WEC have been yet tested in North American waters, and those test sites are all located in USA territories such as Hawaii, Oregon, North Carolina, and New Hampshire (see Section 4).

3.2.2 South america

The geographical distribution of the wave energy resource in South America is strongly associated with latitude. The maximum resource happens on the southern coasts and decreases significantly towards the equator. The importance of latitude in the spatial distribution of wave power is especially obvious on the west coast, especially in Chile, which constitutes the South American country whose coasts receive the highest power carried along predominant swell waves (wave power level increases from 20 to 100 kW/m, as the latitude increases) (Monárdez et al., 2008; Lucero et al., 2017).

Moreover, the variability of the resource is relatively scarce during the various seasons, which makes the Chilenean coast one of the most appealing for the exploitation of wave energy. To get further insights about the technical potential of the resource, an estimate of the output power of some wave energy converters on the market was performed by Monárdez et al. (Monárdez et al., 2008; Mazzaretto et al., 2020). Northwards along the west coast, the wave resource decreases, although relatively significant power can still be found in the coastal waters of Peru, Ecuador and Mexico (Gorr-Pozzi et al., 2021). The rich marine resources along the Chilenean coasts encouraged the Marine Energy Research and Innovation Center (MERIC) creation in 2015.

An assessment of the wave resource in deep waters along the Argentinian coastline and the project's progress of the first WEC in Argentina can be found in (Das Neves Guerreiro and Chandare, 2010).

On the east coast, Brazil is the country receiving the most energetic seas, where the total theoretical potential of wave energy has been estimated to be 91.8 GW along the whole coastline. A substantially lower resource characterizes Argentina, Uruguay, and the northern countries in this hemisphere. Along the Brazilian coast, swell waves are more prevalent and carry more energy in the offshore areas, while wind sea waves dominate the nearshore regions, especially along the northern coast (Sa Cortim et al., 2022). However, the southern coasts of the country (covering the regions of Rio Grande do Sul, Santa Catarina, and Paraná) receive the most energetic waves, with annual average power values estimated at around 21 kW/m (Shadman et al., 2019).

Three ocean renewable energy projects are being carried out in Brazil. One is a prototype of a hyperbaric wave converter installed over a breakwater developed by the Federal University of Rio de Janeiro (UFRJ), which had a full-scale single device of this technology installed in 2011 in Pecém port (Ceará). The device was decommissioned after six months of operation due to the port extension project, but the project is expected to have continuity. Another project is a nearshore wave energy converter at the R&D stage (also by the UFRJ), which is expected to be installed about 25–30 m water depth off the Rio de Janeiro coast (Shadman et al., 2019).

A deeper review of the status and future perspectives for harnessing the wave energy in South America is given in (Shadman et al., 2023). The active, decommissioned, and planned projects, research groups and laboratory infrastructures are presented. Despite the great potential for offshore renewable energy on the South American coasts, these resources have not been explored commercially. Thus, larger investment, an adequate legal framework and more full-scale demonstration projects at sea are necessary to keep moving forward.

3.2.3 Oceania

Wave power in Australia is most significant along the southern Australian shelf, covering the states of Tasmania/Victoria, southern Western Australia, and South Australia (with average values exceeding 30 kW/m). The densely populated coasts of New South Wales and Queensland are also found to be potential sites for wave energy harvesting, with moderate levels of average wave power (10–20 kW/m). Time-average wave power for most of the northern Australian shelf was found to be lower than 10 kW/m. Moreover, nearshore wave energy resources are found to be significant and fairly sustained throughout the year for most of the southern Australian states, with the highest mean wave energy power observed during spring and winter (Hughes and Heap, 2010; Morim et al., 2014). Research using currently available WEC prototypes simulated annual electric power at different coastal locations in the southern and southeast regions (Morim et al., 2014; Liu et al., 2023). The LCOE of wave energy on the Australian southern coast is as low as ~100 $/MWh, and the capacity factor is as high as ~54%. (Morim et al., 2014).

In New Zealand, results of analysing 20 years of hindcast data pointed at average annual wave power values that range significantly in the marine space, from 28 kW/m (at Greymouth) to almost triple that at Invercargill (78 kW/m). Moreover, techno-economic performance indicators were also identified to rank and determine the optimal device for specific locations on the island (Bertram et al., 2020; Albuquerque et al., 2022).

3.2.4 Europe

Europe has been the continent receiving more interest in wave energy exploration research since the late nineties, when the first broad wave energy resource characterization was developed at the European level using a standard methodology and similar wave data set characteristics (Pontes et al., 1996, 1998). The resulting metrics were made available in a user-friendly interactive software. From this characterization, the European offshore resource was computed to be 320 GW (290 GW in the Atlantic coasts and 30 GW in the Mediterranean).

To increase homogeneity on the atmospheric forcing and improve the spatial and temporal resolution of the coarse initial assessments, the HIPOCAS project was initially reported in 2002 (Guedes Soares et al., 2002; Guedes Soares, 2008). Within this project, a database containing climatological parameters and statistics was developed by several authors or entities, who run the WAM model for up to 44 years and developed wave resource assessments with various fine resolution nested grids (spatial resolution varying between 2° offshore and 0.05° in the coastal areas, and temporal resolutions between 1 and 3 hours), in different regional European seas: the Southern North Sea (Weisse et al., 2002; Weisse and Günther, 2007); a small region in the German Bight (Gaslikova and Weisse, 2006); the Mediterranean basin (Sotillo et al., 2005; Ratsimandresy et al., 2008); the North East Atlantic, including Azores and Canary Islands (Pilar et al., 2008; Iglesias and Carballo, 2010, 2011); the Western Iberian Coast (Rusu et al., 2008), the Black Sea (Cherneva et al., 2008), the Baltic Sea (Cieślikiewicz and Paplińska-Swerpel, 2008); and in the Irish (Vijaykumar et al., 2004).

From these results, several locations in Europe were spotted as locations of great interest for wave energy exploration in terms of power density, especially on the West European Atlantic coast. The most attractive locations have pointed at the coasts of Ireland, UK, France, Galicia (Spain), and Portugal (Gleizon et al., 2017).

In Ireland, a mean theoretical power flux between 50 and 60 kW/m was found on the West Coast, within 25 km of the Mayo and Kerry coasts (ESBI 2005), where the West Wave test site is located. At the local scale, average annual power densities of 50 kW/m and 3 kW/m were estimated at the WestWave, Galway Bay (GBTS) and Killar Point test sites, respectively (Atan et al., 2018). North Ireland presents higher energy values measuring up to 160 kW/m, at the nearshore area of Belmullet (Bento et al., 2011). These values tend to decline quickly when moving toward the Irish Sea at the east, which suffers from the island's shadow effect and where the same parameter was as low as 10 kW/m. Although wind waves are the main contributor to annual average wave power density in some regions of this area (Arinaga and Cheung, 2012), the wave climate off Ireland's North and West coasts was determined to be one of the most favourable environments for potential wave energy exploration.

In the UK, up to 95 TWh/yr of wave energy was estimated to be theoretically possible to extract from offshore sites in UK waters. In contrast, the energy that could practically and economically be extracted was found to be between 32 and 42 TW/yr (Carbon Trust 2012). Studies clearly suggest that both Cornwall and the North and West Coasts of Scotland are the most attractive sites for offshore devices, especially in places such as The Hebrides, Orkney, and Pentland Firth. Near the Hebrides and Shetlands shores, the wave power spatial distribution was estimated to be between 40 and 45 kW/m, with maximum values of up to 650 kW/m. For Orkney, the annual wave power density was estimated between 10 and 35 kW/m (Neill et al., 2014, Venugopal and Nemalidinne 2015). The theoretical and technical wave resource in Scotland, as well as an overview of commercial progress has been examined in (Neill et al., 2017). In the region of Cornwall, several wave power characterizations were deployed as well, with a special focus on the Wave Hub & FAB test sites (Smith et al. 2013, van Nieuwkoop et al., 2013, Fairley et al., 2017), in which various wave energy converters have already been tested (see Section 5). The results showed that the most energetic waves, and therefore the wave power, are more significant in the southwest corner of the region (van Nieuwkoop et al., 2013). The contribution to power levels from the northerly waves decreases moving eastward along the north coast of Cornwall and into the South Wales locations due to the decreased fetch, whereas southerly sea states show increasing levels of power at the Welsh locations (Fairley et al., 2017). Thus, the west side of the Isles of Scilly was characterized by a mean wave power of approximately 30 kW/m, the northwest-facing Cornish coast with approximately 10–25 kW/m, and the southeast-facing Cornish coast with about 2–15 kW/m. The LCOE of wave energy farms in the Irish and western UK waters was estimated by (O'Connell et al., 2020), considering different technology types and the geospatially variable inputs at play. The results reveal areas of high project feasibility off the west coast of Ireland, the Celtic Sea and the Inner Seas off the West Coast of Scotland, with LCOE values below 110 €/MWh along the shores of these areas (O'Connell, 2024).

In the North Sea, which is characterized by shallow waters with a mean water depth of 90 metres, most parts are hardly shaded by the UK. Wave power resource was found to exceed 15 kW/m in very nearshore areas, and it declines steadily when moving southwards, near the English Channel, where the values were found at approximately 5 kW/m. Only the resources in the most exposed northern part of the North Sea were comparable to those of the West European coast. However, the relevance of a softer wave climate and the accessible properties of the North Sea confer beneficial properties for the development and installation of WECs, even if it has been previously overlooked (Lavidas and Polinder, 2019).

In France, most of the research evaluating the wave energy resource was carried out over the French West Coast, in the Bay of Biscay. Results suggest a significant amount of energy resources around Le Croisic, between 25 and 30 kW/m (Mattarolo et al., 2009; Gonçalves et al., 2014a, 2018). Located in the offshore waters of Le Croisic, the grid-connected SEM-REV test site offers operational conditions for WEC and wind turbine demonstrations. However, the Iroise Sea has also been pointed out as one of the most interesting areas for extracting marine renewable energy in France and Europe, despite its heavy marine traffic, fishing activities and recreation. Studies showed that the annual average wave power can reach up to 45 kW/m (Smith and Maisondieu, 2014).

In Spain, the highest energetic area is around the Galician coast, accounting for approximately 35–40 kW/m of mean wave power in deep waters (Losada et al., 2010; Bento et al., 2012, 2018). The mean wave power density decreases west to east, with the deep-water areas along the Cantabrian Coast receiving around 30 kW/m.

The Basque Country currently counts two wave energy generation test sites: BiMEP (located at the northern coast of Bilbao), and Mutriku (located more eastern between the cities of Bilbao and San Sebastian). BiMEP hosted the first grid-connected offshore wave energy converter in Spain and one of the first in the world, the point absorber MARMOK-A-5 (Thomaz et al., 2019). This device was set up about 4 km offshore and is delivering electrical energy to the grid from December 2016 to June 2019. Thomaz et al. (2019) present an O&M model calibrated with actual data from this wave energy device and estimate socioeconomic indexes, such as the LCOE of this device, for different case studies. On the other hand, the Mutriku is a wave energy generating and testing plant with 14 OWC devices located at a breakwater that came into operation in 2011. It is the only wave farm in the world supplying electricity to the grid about 74.4% of the time, still up to this date. Its main operational aspects, such as its average capacity factor and seasonal variability, have been reported by (Ibarra-Berastegi et al., 2018; Serras et al., 2019).

For the Mediterranean and South Atlantic coast, average wave power values were estimated at 8 kW/m or less. The wave energy was also found to vary from deep water to the shallows, and the coastal shape and bathymetry produced local wave energy concentrations in some areas.

In Portugal, a typical annual average wave power of 25 kW/m was estimated by Pontes et al. (2005), with higher wave heights and power happening at unsheltered sites. The trend identified was that the wave energy is highest in the north and decreases slightly towards the south. The same trend would be later identified in further studies (Rusu and Guedes Soares, 2009; Silva et al., 2013, 2015, 2018; Bento et al., 2014). The efficiency of different WECs along the Portuguese and Galician coasts for a near future scenario was evaluated in (Ribeiro et al., 2020). Results concluded that both the wave power resource and the electric power capacity are expected to decrease in the near future, while the capture width and cost of energy will increase.

Nowadays, a few areas off the Portuguese continental coast serve to support the testing of offshore wave and wind energy prototypes and farms for ocean energy companies. The "Ocean Plug- Portuguese Pilot Zone" was first set up in São Pedro de Moel (Leiria) and later moved to Viana do Castelo (northern coast), where it presently seats in depths between 85 and 100 m (Ocean Plug, 2021). This project was the worldwide pioneer in implementing a maritime zone to install pre-commercial and commercial phases of WECs. A small area about 900 m out of the coast of Peniche is currently hosting an experimental test of the WaveRoller WEC (WaveRoller, 2021), and a cooperative OceanLab in Agucadoura is presently being established to support future marine energy technology experiments.

The wave energy resource is also significant over the European Atlantic Islands (Canary Islands, Madeira, Açores and Iceland). Various authors studied the wave energy potential in the Canary Islands (Chiri et al., 2013; Gonçalves et al., 2014b, 2020; Rusu, 2014; Rodríguez et al., 2015), and determined a significant space variability around the archipelago, with the North and Northeast sides of the islands presenting higher average annual values of available wave energy (20–32 kW/m), compared to the Southern areas (4–13 kW/m) (Fernández Prieto et al., 2019).

Regarding the Portuguese territories, detailed assessments resulted on annual average power densities of 30–60 kW/m in the Azores (Rusu and Guedes Soares, 2012b; Gonçalves and Guedes Soares, 2021); and an average of 14 kW/m in Madeira Islands (Rusu and Guedes Soares, 2012a). Assessments were also performed to evaluate the practicable resource and the marine space availability for the nearshore and offshore wave energy exploration in the Azorean archipelago (Ramos et al., 2021) and the techno-economic suitability of marine areas around Madeira for the exploration of wave energy (Ramos et al., 2020).

Further up to the north, Iceland and the Faroe Islands are particularly interesting locations for wave energy exploration, as those islands are completely self-reliant and have no interconnections with other countries. In Iceland, the southern areas of the island were found to be more appealing for the deployment of a WEC farm, as the average Pw in four decades was found to be 59 kW/m, significantly higher compared to less the 10 kW/m in the northern areas (Penalba et al., 2020). For the Faroe Islands, the local wave power potential has been analysed by (Joensen et al., 2021), who found the average wave energy flux at nearshore locations to the west and north shores to be 45–55 kW/m, while significantly lower flux of 10–25 kW/m was found at eastern locations.

An extended overview of the wave energy resource characterization in Europe refer to (Ramos-Marin and Guedes Soares 2024, Lavidas and Venugopal 2018a).

3.2.5 Africa

The African continent has received, by far, the least interest in wave energy resource assessment (despite Antarctica) due to its less developed energetic framework and economy. However, some authors evaluated the resources on the Moroccan and South African coasts. Ocean wave energy has been found available all over the Atlantic Moroccan coastline (average wave power up to 30 kW/m and average annual wave energy up to 262 MW h/m), with peaks between the regions of Essaouira and Agadir where the wave heights are between 1.9 and 2.13 m (Sierra et al., 2016; Alaoui, 2019). The wave energy is relatively abundant in the region of Casa Blanca as well, with an average annual wave potential of about 22 kW/m (Mouakkir et al., 2022). Nonetheless, the resource is slightly lower than in the neighbouring Canary Islands. A considerable seasonal trend has been found, with the wave energy resource over four times greater in winter than summer (Sierra et al., 2016).

In South Africa, the predominant wave energy is mainly originated from the Southeast swell components. This phenomenon makes nearshore magnitudes of wave power slightly higher for the South-eastern coast (15–20 kW/m) than for the Western coast (5–10 kW/m), where the complex orography increases the non-linear interactions reducing the wave power levels (Lavidas and Venugopal, 2018b). Previous results estimated that the coast of Cape Nature Walker Bay would be the most effective for South Africa's wave energy farm deployments (Wang and Nhieu, 2023).

In the coastal areas of the Cape Verde archipelago, the wave energy potential has also been spotted significantly, with mean wave power densities over 7 kW/ m (Bernardino et al., 2017).

3.2.6 Asia

The highest wave energy resource in Asia is concentrated in the Pacific coasts of eastern Japan and the Russian Bering Sea ($Hs \approx 2-3$ m, $Tp \approx 7-9$ s, $Pw \approx 20-40$ kW/m) (Martinez and Iglesias, 2020; Rusu and Rusu, 2021).

In Japan, some areas offshore Kamaishi and Oarai have been catalogued as favourable for wave energy generation, because its average wave density levels (>10 kW/m) and low seasonality variations. Indeed, WEC tests have already been performed or are planned for these regions adjacent to cities with large energy consumption. Areas near the Izu Island and east of the Ryukyu might also be suitable for installation of a small number of WECs (since the local energy consumption is lower) (Webb et al., 2020).

In the South Korean Peninsula, the average annual resource in different regions has been characterized by Kim et al. (Kim et al., 2012) as follows: Yellow Sea (0.6–13.3 kW/m), Korea Strait (3–9 kW/m) and East Sea (3–8 kW/m). However, it was found that the wave energy is the highest in the vicinity of Jeju Island (7–12 kW/m).

Less energetic seas characterize the coasts of south-eastern China, north-eastern Indonesia, and the Philippines ($Hs \approx 1$–2 m, $Tp \approx 4$–8 s, $Pw \approx 2$–20 kW/m) (Martinez and Iglesias, 2020; Rusu and Rusu, 2021).

Along Chinese coasts, the spatial distribution of ocean wave power is uneven. The wave power density increases from north to south and from the nearshore to the offshore waters. The wave potential is less than 2 kW/m in most areas of the Bohai Sea. The average value for the northern and nearshore areas of the Yellow Sea is 1–2 kW/m, while it is 2–3 kW/m offshore for the southern part. For the East China Sea, the wave power density is generally greater than 2 kW/m around the Zhejiang Province, and for the south part, such as on Dachen Island, it is greater than 3 kW/m. For the northern part of the South China Sea along the coastline of Guangdong Province and Hainan Island, this value is generally between 3 and 5 kW/m (Qiu et al., 2019). From a global perspective, these low values make wave energy development a challenge in China. Thus, different means should be taken to design small-scale WECs suitable for China's low wave power density.

However, wave power density has been found to be remarkable in areas such as the southeast of Vietnam coasts, although with significant intra-annual variability (ranging from 2 to 40 kW/m) (Kamranzad and Lin, 2020). Other areas with more abundant and stable wave power density are in the north-central part of the South China Sea, the Luzon Strait, and southeast of Taiwan (mean annual power ranging from 14.0–18.5 kW/m) (Wan et al., 2015). Mainly Taiwan has been characterized as having the most abundant wave resource in China, which is 4.3 GW, but ocean energy remains relatively unexplored there due to the lack of technological development and special financial support (Wang et al., 2011). Some specific regions, such as Xiashan Island, Nanlu Island, Yun'ao and Zhelang, have been prioritized for the potential exploitation of wave energy because of their relatively higher energy density, lower seasonal variation, small mean range of tide, deep nearshore water, petrous seaboard, and steep slopes. A wave energy testing site (NOITS) is being developed by the National Ocean Technology Center in Weihai (Shandong Province) to facilitate testing scaled wave and tidal energy converters in an open sea environment. The analysis of the wave resource and its spatio-temporal distribution in this site has already been the subject of study by some authors (Fang et al., 2022). For a review of the main achievements of the past several decades, present relevant policies and projects that have been conducted in China refer to (Wang et al., 2011; Qiu et al., 2019).

In Indonesia, mean wave energy has been classified based on meteorological seasons, and it was found that the most energetic months are June, July, and August for all areas of south, southwest and west of Indonesia, where it can exceed 30 kW/m. In some locations like the south of Jawa Island, Bali Island and West Nusa Tenggara, wave energy is available throughout the entire year, while in the region of west Sumatera, promising wave energy is available during the time from March to November (Ribal et al., 2020).

In Malaysia, assessments show that the average wave energy density of the coasts facing the South China Sea ranges from.41 kW/m to 7.92 kW/m (Yaakob et al., 2016).

Finally, studies have evaluated the wave resource along the coasts of India (Sanil Kumar and Anoop, 2015; Sannasiraj and Sundar, 2016; Patel et al., 2020), finding the mean annual wave power along the eastern Indian shelf seas between 2 and 4 kW/m, lower than the mean yearly wave power along the western part (9–12 kW/m). During the monsoon season, the maximum potential at times reached 30 kW/m (Patel et al., 2020). Three potential sites for harnessing wave energy and its techno-economic feasibility using four different wave energy converters were also identified, pointing at a maximum capacity factor of about 22–31% and a minimum LCOE between 354 and 505 €/MWh at selected hotspots (Patel et al., 2022).

An overview of wave energy research in and around the Indian Ocean is given in Alam et al., (2024).

3.2.7 Enclosed and semi-enclosed basins

Enclosed and semi-enclosed basins represent the least energetic seas globally, where waves are often small, short-crested, and strongly dependent on wind forcing, as limited space and fetch lengths prevent waves from evolving to swell.

However, although characterized by low wave power density levels, existing research states that the wave energy can be successfully exploited if properly downscaling some state-of-the-art WEC technologies (Bozzi et al., 2018). Consequently, the wave resources in these basins have been the object of analysis in several studies (see Supplementary Material 2).

Estimates in the Black Sea indicate approximate values of time average power density between 1.6 and 6 kW/m and significant wave height between 0.6 and 1m (Akpınar et al., 2017; Rusu 2018). The Baltic Sea presents an average annual $Hs < 1.5$ m and $Pw \approx 0.7$–1.5 kW/m (Björkqvist et al. 2014, 2018). In the Red Sea, average power density levels of about 4.5 kW/m were estimated (Aboobacker et al., 2017). The Persian Gulf in western Asia represents mean power density values below 2 kW/m (Goharnejad et al., 2021).

In the Mediterranean Sea, waves have been characterized by average Hs ranging from 0.05–1.2 (Soukissian et al., 2017) 5 and $Pw \approx 2$–12 kW/m. Nonetheless, all Mediterranean basin is characterized by a strong variability on monthly base, which results in relevant fluctuations on a seasonal base.

Several studies have evaluated the wave resource for energy exploitation across the Mediterranean basin (Liberti et al., 2013; Besio et al., 2016; Soukissian et al., 2017; Lavidas et al., 2016, 2018a; Bozzi et al., 2018; Ferrari et al., 2020; Acar et al., 2023). Some of them focused specifically in one of the internal regions or seas: Balearic Sea (Sierra et al., 2014; Ponce de Leon et al., 2016), Ligurian Sea (Lira-Loarca et al., 2022), Sea of Sicily (Monteforte et al., 2015), Eastern Mediterranean (Ayat, 2013), Ionian and Aegean Seas (Emmanouil et al., 2016; Jadidoleslam et al., 2016; (Lavidas & Venugopal 2017a; Kozyrakis et al., 2023), the Levantine Basin (Zodiatis et al., 2014), and the African coasts of Algeria and Libya (Amarouche et al., 2020; Lavidas & Venugopal, 2017b). Generally, the average wave energy flux in the Mediterranean ranges from a few kW/m in the less dynamic regions (Alboran Sea, Adriatic Sea, Aegean Sea) to over 10 kW/m in the Central Mediterranean, specifically between the Balearic Islands and Sardinia. Certain areas, such as the Eastern Mediterranean, can be considered moderately energetic, exhibiting values of the available energy flux between 6 and 9 kW/m (Besio et al., 2016). Although the area extending between Sardinia and the Balearic Islands has been historically characterized as the most energetic in the Mediterranean, this area represents a quite low efficiency for WECs because extreme and rare events provide a large part of the available energy (Soukissian et al., 2017; Bozzi et al., 2018). Conversely, coastal areas in the Gulf of Lion, the Sicily channel, the Alboran Sea, the Libyan coast, Crete and Cyprus represent the best performance for scaled WEC technologies (Bozzi et al., 2018). Interestingly, the exploitation of coupled offshore wind-wave energy in the region of the Algerian Coast has been found especially advantageous over the sole exploitation of one energy type, as it lowers the variability of the available resource (Ferrari et al., 2020).

In the Gulf of Oman, the spatial distribution of wave power increases from west to east towards the Indian Ocean and the surroundings of the port of Chabahar is suggested as the best area for the installation of a wave farm (Saket and Etemad-Shahidi, 2012; Kamranzad et al., 2016a; Pourali et al., 2023). Finally, in the Caspian Sea (located between Asia and Europe), the richest area of wave energy potential is in the central part of the southern sea, with maximum values of 1.5 kW/m of mean wave power (Kamranzad et al., 2016b). Due to those low levels of wave power, wind energy resources have been found to have a greater potential in the coastal environment (Rusu and Onea, 2013).

4 World test facilities

Throughout the last decades, several test sites included in Figure 7 have been globally established to support the actual testing of different WEC devices and prototypes in the open sea. Extended details about the spatial characteristics of the test sites, wave resource characterizations and status are included in Table S3.1 (Supplementary Material 3). Further information can also be found in (SOWFIA 2011, Aderinto and Li 2019, May-Varas and Robertson 2020) and (Tethys, 2022a).

Recently, a data platform known as MARENDATA (Hidromod, 2020) has been made available, enabling access to a marine energy resource repository and impact assessment raw data from different test sites within the European NE Atlantic region. It can be used to find detailed information on a particular marine energy project test site or to view data regarding one or multiple environmental parameters at different test centres. Similarly, another open access tool has been created, which permits interactive assessment of the suitability of wave energy projects in different European regions in terms of the potential impacts that they can cause, and other criteria related to the practicable potential of the wave resource. It is named WEC-ERA and has been built within the scope of the WESE project (WESE Project, 2021). The tool visualises the pressures and ecological risks of three different wave energy converter technologies during their life-cycle stages–from installation to operation and decommissioning.

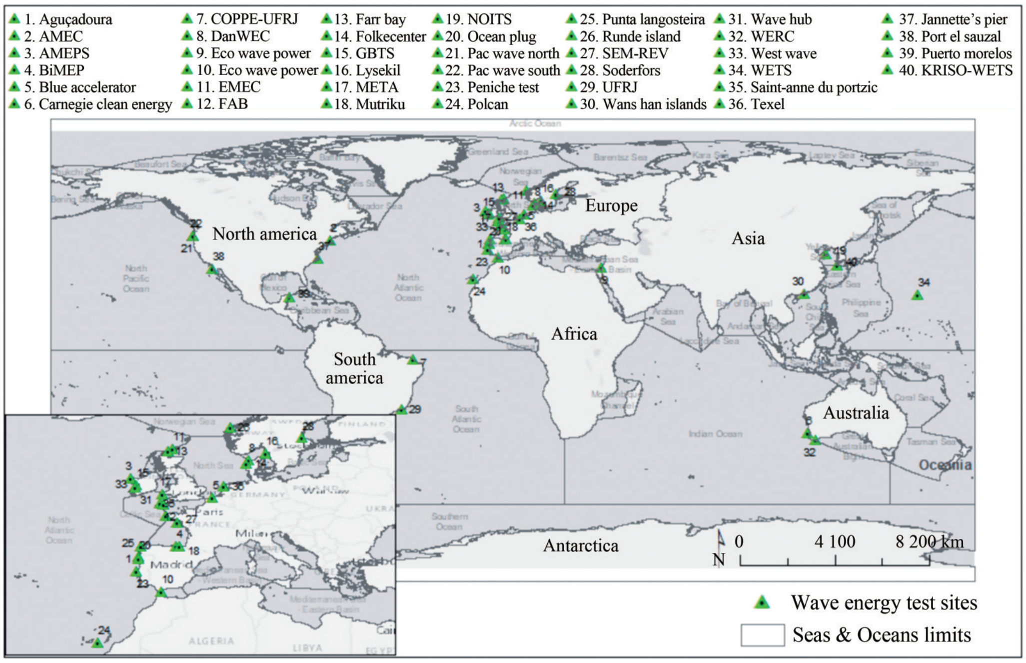


Figure 7 World wave energy test sites

5 Conclusions

The main approaches and metrics used for the wave energy resource characterization for exploitation at different levels have been reviewed, as well as existing global and continental wave energy resource assessments and wave energy test sites around the world.

Most of the existing research has focused on describing the wave energy potential at the theoretical level of the resource. Although early wave characterizations relied on observed in-situ data from buoys and other measurement devices, nowadays, numerical modelling has become the most popular methodology for wave resource assessment. Satellite imagery has also increased in popularity and is expected to become more used as the frequency and coverage of satellite imagery expands. Numerical modelling allows the computation of spectral or integrated wave parameters (wave height, period, and direction), which are fundamental metrics in every resource assessment. Those parameters have further been used to compute a wide variety of adequacy indexes and metrics for wave energy exploitation. No specific metric has yet been established as preferred for the evaluation of the wave energy resource to determine an adequate location and technology for energy exploitation. However, a significant part of existing research converges into determining the available wave power density to theoretically evaluate the wave energy resource. Bivariate occurrence diagrams, coefficient of variation, and temporal variability indexes have also been rather common metrics at this level. This convergence allows to compare and evaluate the resources in different regions.

Nonetheless, when it comes to analysing the potential of the wave energy for exploitation purposes, the computation of metrics at the theoretical level is not sufficient, especially in wave farm feasibility and design assessments at local scales. Other performance metrics and indexes at the practicable, technical, and socio-economic levels should be computed in both spatial and temporal domains at a sufficient resolution to accomplish a comprehensive wave resource assessment for exploitation. Marine spatial planning techniques are frequently needed to explore marine space availability to exploit wave energy at a practicable level. The net wave power output, the capacity factor, and capture width are some of the metrics most frequently assessed at the technical level, and the levelized cost of energy is the most conventional index at the socio-economic level. Recent publications have considered different index classification systems and multi-criteria techniques as useful approaches that enable the creation of spatial rankings of adequacy and the combined consideration of different metrics belonging to different resource levels.

The temporal and spatial variability of such metrics should also be carefully analysed, as it greatly influences the adequacy of a region for wave energy exploitation. Although in recent years, modelling approaches have become more sophisticated and efforts have been made towards the standardization of numerical simulations to perform appropriate wave resource and climate characterizations (such as the specifications proposed by the IEC-62600-101), a great number of studies still do not comply with the specified input data span, or with the temporal, spatial and frequency resolutions. The use of short-term datasets increases intra-annual and decadal variation uncertainties. Similarly, coarse characterizations are not appropriate for capturing the spatial variations of the wave resource at nearshore and local scales, especially at irregular bathymetries and coastal geography.

Consensually, existing global research points at global temperate regions of both hemispheres as those where the highest wave power density is concentrated. The South Hemisphere has been characterized by slightly higher mean annual wave power than the North Hemisphere, and the areas where the largest wave power density occurs are located at offshore regions of southern Australia, New Zealand, South Africa, Chile, North-west Europe, Iceland, and Greenland those characterized by the highest power densities. The lowest wave energy density is attributed to the Pacific equatorial waters and the enclosed and semi-enclosed basin.

Nonetheless, when considering other metrics at the practicable, technical, and socio-economic level (and their temporal and spatial variability), some references have suggested that regions previously neglected due to their perceived "milder" theoretical resource may, in fact, constitute "hidden opportunities" where wave farms could show better performance than other regions, especially if considering the proper scalation of wave energy converters.

Although great efforts have been put into wave energy exploration research and several wave energy converters have already been tested in the open sea, no convergence yet exist towards the most efficient technology. Thus, the exploitation of wave energy is still not matured in terms of grid integration, mass production, and, thus, far-off commercialization.

Overall, regions within the European Union have received the most significant interest in wave energy exploration research (encouraged by governmental interest and special public funding). Moreover, Europe has led the progression towards commercialising wave energy as it has the most significant number of wave energy test sites. Conversely, research in coastal regions of less developed or populated areas, such as middle Africa and Antarctica, is relatively scarce.

Nomenclature

ACF	Accessibility Factor (%)
ADCP	Acoustic Doppler Current Profiler
Af	Availability Factor (also Downtime Index) (%)
AVI	Annual Variability Index
BFI	Benjamin-Feir Index
Cf	Capacity Factor
CoV	Coefficient of Variation
CT	Cliff Topography
Cw	Capture Width (m)
Cw_R	Capture Width Ratio
DP	Distance to Ports (km)
DS	Distance to Shore (km)
D_{sub}	Distance to inland electric substations (km)
ECMW	European Centre for Medium-Range Weather Forecasts
E_i	Efficiency Index
EI	Exploitability Index
Env_c	Environmental constrains
Eo	Energy Output (kWh)
EPBT	Energy Payback Time
EROI	Energy Return on Investment
Ew	Wave Energy Density (J/m^2) or (kW s m^{-2})
FDP	Frequency and Directionally constrained Power classification classes
f_m	Mean spectral frequency (Hz) or (s^{-1})
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FP	Frequency constrained Power classification classes
f_p	Peak Spectral frequency (Hz) or (s^{-1})
GOWAF	Global Ocean Waves Analysis and Forecast
HCMR	Hellenic Centre for Marine Research
Hs	Significant wave height (m)
H_{swell}	Swell Wave Height (m)
IFREMER	French Institute for Ocean Science
IHCantabria	Institute of Environmental Hydraulics Cantabria
I_k	Wave energy resource index
IRR	Internal Rate of Return (%)
JMA	Japan Meteorological Agency
LCA	Life Cost Analysis
LCOE	Levelized Cost of Energy (€/kWh)
LRM	Low Resolution Mode altimeter
MBPC	Max Band Power Classification
MCA	Multi-Criteria Analysis
m^n	N-th spectral moment (m^2 s^n)
MVI	Monthly Variability Index
NCEP/NCAR	National Centers for Environmental Prediction/ National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value (€)
OHI	Optimum hotspot identifier
OP_{ht}	Occurrence bivariate diagrams (%) or (hr)
OU	Other Marine Uses
Pd	Delivered Power (kW)
Po	Power Output (kW)
Po_n	Dimensionless normalized net power output
Pw	Wave Power Density (kW/m)
Pw_{exp}	Exploitable power (%)

Pw_n	Normalized Wave Power Density
R (wind, wave)$_i$	Correlation coefficient (wind and wave)
RE	Renewable Energy
REP	Annual energy production per unit of rated power (Wh/W)
RoC	Rate of Change
Rr	Relative Risk
$S(f)$	Wave spectral density (m^2s)
$S(f, \theta)$	Directional wave spectral density (m2s rad^{-1})
SAR	Synthetic Aperture Radar altimeter
SCOE	Socio-economic Cost Assessment (Nr jobs) or (€)
SG	Seabed Geology
SI_p	Climate-dependent Sustainability Index
SIWED	Selection Index for Wave Energy Deployments
Ss	Suitability Score
Stats	Long-term statistics and extreme value analysis
S_{th}	Survivability threshold
SVI	Seasonal Variability Index
Te	Energy period (s)
t_i	Inter-annual Variability Index
Tm	Mean period (s)
Tp	Peak spectral period (s)
Ts	Significant period (s)
TWPC	Total Wave Power Classification
Tz	Zero-crossing period (s)
U	Degree of Utilization (%)
Uf	Utilization factor (%)
Uw_c	Underwater cables
WD	Water Depth (m)
WDW	Wave Directional Width
WEC	Wave Energy Converter
WEDI	Wave Energy Development Index
WEI	Wave Exploitability Index
w_m	Mean spectral angular frequency (rad s^{-1})
w_p	Spectral angular frequency (rad s^{-1})
w_z	Zero-crossing angular frequency (rad s^{-1})
β_P	Sea state steepness
θ_m	Mean direction (rad)
θ_p	Peak direction (rad)
$\sigma_\theta(f)$	Mean directional spread over frequencies

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References

Aboobacker VM, Shanas PR, Alsaafani MA, Albarakati AMA (2017) Wave energy resource assessment for Red Sea. Renewable Energy 114: 46-58. https://doi.org/10.1016/j.renene.2016.09.073

ABP MER (2008) Atlas of UK Marine Renewable Energy Resources. http://www.renewables-atlas.info/[Accessed 12 Nov 2021]

Aderinto T, Li H (2019) Review on power performance and efficiency of wave energy converters. Energies 12(22). https://doi.org/10.3390/en12224329

Ahamed R, McKee K, Howard I (2020) Advancements of wave energy converters based on power take off (PTO) systems: A review. Ocean Engineering 204: 107-248. https://doi.org/10.1016/ j.oceaneng.2020.107248

Ahn S, Haas KA, Neary VS (2019) Wave energy resource classification system for US coastal waters. Renewable and Sustainable Energy Reviews 104: 54-68. https://doi.org/10.1016/j.rser.2019.01.017

Ahn S, Haas KA, Neary VS (2020) Wave energy resource characterization and assessment for coastal waters of the United States. Applied Energy 267 (3): 114922. https://doi.org/10.1016/j.apenergy.2020.114922

Ahn S, Neary VS, Haas KA (2022) Global wave energy resource classification system for regional energy planning and project development. Renewable and Sustainable Energy Reviews 162. https://doi.org/10.1016/j.rser.2022.112438

Akpınar A, Bingölbali B, van Vledder GP (2017) Long-term analysis of wave power potential in the Black Sea, based on 31-year SWAN simulations. Ocean Engineering 130: 482-497

Alam M, Kayes I, Hasan A, Shahriar T, Habib MA (2024) Exploring SAARC's ocean energy potential: Current status and future policies. Energy Reports 11: 754-778. https://doi.org/10.1016/j.oceaneng.2016.12.023

Alaoui C (2019) Review and assessment of offshore renewable energy resources in Morocco's coastline. Cogent Engineering 6(1). https://doi.org/10.1080/23311916.2019.1654659

Albuquerque J, Antolínez JAA, Méndez FJ, Coco G (2022) On the projected changes in New Zealand's wave climate and its main drivers. New Zealand Journal of Marine and Freshwater Research 58(1): 89-126. https://doi.org/10.1080/00288330.2022. 2135116

Alday M, Accensi M, Ardhuin F, Dodet G (2021) A global wave parameter database for geophysical applications. Part 3: Improved forcing and spectral resolution. Ocean Modelling 166. https://doi.org/10.1016/j.ocemod.2021.101848

Amarouche K, Akpınar A, Bachari NEI, Houma F (2020) Wave energy resource assessment along the Algerian coast based on 39-year wave hindcast. Renewable Energy 153: 840-860. https://doi.org/10.1016/j.renene.2020.02.040

Andersen K, Chapman A, Hareide NR, Folkestad AO, Sparrevik E, Langhamer O (2009) Environmental Monitoring at the Maren Wave Power Test Site off the Island of Runde, Western Norway: Planning and Design. In: Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweeden 1029-1038

Arinaga RA, Cheung KF (2012) Atlas of global wave energy from 10 years of reanalysis and hindcast data. Renewable Energy 39(1): 49-64. https://doi.org/10.1016/j.renene.2011.06.039

Atan R, Goggins J, Nash S (2016) A detailed assessment of the wave energy resource at the Atlantic Marine Energy Test Site. Energies 9(11). https://doi.org/10.3390/en9110967

Atan R, Goggins J, Nash S (2018) Galway Bay–The 1/4 scale wave energy test site? A detailed wave energy resource assessment and investigation of scaling factors. Renewable Energy 119: 217-234.

https://doi.org/10.1016/j.renene.2017.11.090
Australian Marine Energy Atlas [online] (2022) https://nationalmap.gov.au/[Accessed 4 Nov 2022]
Ayat B (2013) Wave power atlas of Eastern Mediterranean and Aegean Seas. Energy 54: 251-262. https://doi.org/10.1016/j.energy.2013.02.060
Barstow S, Mørk G, Lønseth L, Mathisen JP (2009) WorldWaves wave energy resource assessments from the deep ocean to the coast. Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden 149-159
Barstow S, Mørk G, Lønseth L, Schjølberg P, Machado U, Athanassoulis G, Belibassakis K, Gerostathis T, Stefanakos C, Spaan G (2003) WORLDWAVES: Fusion of data from many sources in a user-friendly software package for timely calculation of wave statistics in global coastal waters. Proceedings of the International Offshore and Polar Engineering Conference 1481-1488
Barstow S, Mørk G, Mollison D, Cruz J (2008) The Wave Energy Resource. In: J. Cruz, ed. Ocean Wave Energy: Current Status and Future Perspectives. Berlin, Heidelberg: Springer Berlin Heidelberg 93-132. https://doi.org/10.1007/978-3-540-74895-3_4
Barua A, Salauddin Rasel M (2024) Advances and challenges in ocean wave energy harvesting. Sustainable Energy Technologies and Assessments 61: 103599. https://doi. org/10.1016/j. seta. 2023. 103599
Bento AR, Martinho P, Campos R, Guedes Soares C (2011) Modelling wave energy resources in the Irish West Coast. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering-OMAE 945-953. https://doi.org/10.1115/OMAE2011-50346
Bento AR, Martinho P, Guedes Soares C (2012) Modelling wave energy for the north coast of Spain. Maritime Engineering and Technology-Proceedings of 1st International Conference on Maritime Technology and Engineering 563-570
Bento AR, Martinho P, Guedes Soares C (2018) Wave energy assessment for Northern Spain from a 33-year hindcast. Renewable Energy 127: 322-333. https://doi.org/10.1016/j.renene.2018.04.049
Bento AR, Rusu E, Martinho P, Guedes Soares C (2014) Assessment of the changes induced by a wave energy farm in the nearshore wave conditions. Computers and Geosciences 71(1): 50-61. https://doi.org/10.1016/j.cageo.2014.03.006
Bernardino M, Rusu L, Guedes Soares C (2017) Evaluation of the wave energy resources in the Cape Verde Islands. Renewable Energy 101: 316-326. https://doi.org/10.1016/j.renene.2016.08.040
Bertram DV, Tarighaleslami AH, Walmsley MRW, Atkins MJ, Glasgow GDE (2020) A systematic approach for selecting suitable wave energy converters for potential wave energy farm sites. Renewable and Sustainable Energy Reviews 132(March): 110011. https://doi.org/10.1016/j.rser.2020.110011
Besio G, Mentaschi L, Mazzino A (2016) Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast. Energy 94: 50-63. https://doi.org/10.1016/j.energy.2015.10.044
Bhaskaran S, Verma AS, Goupee AJ, Bhattacharya S, Nejad AR, Shi W (2023) Comparison of extreme wind and waves using different statistical methods in 40 offshore wind energy lease areas worldwide. Energies 16(19). https://doi.org/10.3390/en16196935
Bhuiyan MA, Hu P, Khare V, Hamaguchi Y, Thakur BK, Rahman MK (2022) Economic feasibility of marine renewable energy: Review. Frontiers in Marine Science. https://doi.org/10.3389/fmars.2022.988513
Björkqvist JV, Lukas I, Alari V, van Vledder GP, Hulst S, Pettersson H, Behrens A, Männik A (2018) Comparing a 41-year model hindcast with decades of wave measurements from the Baltic Sea. Ocean Engineering 152: 57-71. https://doi.org/10.1016/j.oceaneng.2018.01.048
Blue Accelerator [online] (2022) https://www.blueaccelerator.be/[Accessed 16 Nov 2022]
Bozzi S, Besio G, Passoni G (2018) Wave power technologies for the Mediterranean offshore: Scaling and performance analysis. Coastal Engineering 136(January): 130-146. https://doi.org/10.1016/j.coastaleng.2018.03.001
Cahill BG, Lewis T (2013) Wave energy resource characterisation of the Atlantic Marine Energy Test Site. International Journal of Marine Energy 1: 3-15. https://doi.org/10.1016/j.ijome.2013.05.001
Caires S, Sterl A, Komen G, Swail VR (2004) The web-based KNMI/ERA-40 global wave climatology atlas. Bulletin of the World Meteorological Organization 53(1996): 142-146
Caires S, Sterl A (2005) 100-year return value estimates for ocean wind speed and significant wave height from the ERA-40 data. Journal of Climate 18(7): 1032-1048. https://doi.org/10.1175/JCLI-3312.1
Carbon Trust [online] (2012) UK Wave Resource Study. https://www.marineenergywales.co.uk/wp-content/uploads/2016/01/Carbon-Trust-UK-wave-energy-resource-Oct-20121.pdf [Accessed 16 Nov 2022]
Carnegie [online] (2022) Garden Island Microgrid (WA). https://www.carnegiece.com/portfolio/garden-island-microgrid-wa/[Accessed 16 Nov 2022]
CEPS [online] (2022) Wave Energy Test Site. https://ceps. unh. edu/facility/wave-energy-test-site [Accessed 16 Nov 2022]
Chávez V, Bárcenas JF, Martínez ML, Mateos E, Zúñiga-Ríos A, Guimarais M, Wojtarowski A, Landgrave R, Ceballos Canché CH, Silva R (2023) Potential sites for the use of ocean energy in the Mexican Caribbean. Energy Sources, Part B: Economics, Planning and Policy 18(1). https://doi.org/10.1080/15567249.2022.2160524
Chawla A, Spindler DM, Tolman HL (2013) Validation of a thirty-year wave hindcast using the Climate Forecast System Reanalysis winds. Ocean Modelling 70: 189-206. https://doi.org/10.1016/j.ocemod.2012.07.005
Chen W, Liu J, Li J, Sun L, Li B, Xing H, Shi P (2022) Wave energy assessment for the nearshore region of the northern South China Sea based on in situ observations. Energy Reports 8: 149-158. https://doi.org/10.1016/j.egyr.2022.03.068
Chen Z, Yu H, Hu M, Meng G, Wen C (2013) A review of offshore wave energy extraction system. Advances in Mechanical Engineering 2013. https://doi.org/10.1155/2013/623020
Cherneva Z, Andreeva N, Pilar P, Valchev N, Petrova P, Guedes Soares C (2008) Validation of the WAMC4 wave model for the Black Sea. Coastal Engineering 55(11): 881-893. https://doi.org/10.1016/j.coastaleng.2008.02.028
Chiri H, Pacheco M, Rodríguez G (2013) Spatial variability of wave energy resources around the Canary Islands. WIT Transactions on Ecology and the Environment 169: 15-26. https://doi.org/10.2495/13CP0021
Christakos K, Lavidas G, Gao Z, Björkqvist JV (2024) Long-term assessment of wave conditions and wave energy resource in the Arctic Ocean. Renewable Energy 220. https://doi. org/10.1016/j.renene.2023.119678
Cieślikiewicz W, Paplińska-Swerpel B (2008) A 44-year hindcast of wind wave fields over the Baltic Sea. Coastal Engineering 55(11):

894-905. https://doi.org/10.1016/j.coastaleng.2008.02.017

Clemente D, Rosa-Santos P, Taveira-Pinto F (2021) On the potential synergies and applications of wave energy converters: A review. Renewable and Sustainable Energy Reviews 135(July 2020): 110162. https://doi.org/10.1016/j.rser.2020.110162

Copernicus Global Database [online] (2022) https://data.marine.copernicus.eu/viewer [Accessed 4 Nov 2022]

Cornett A (2009) A global wave energy resource assessment. Proceedings of The Eighteenth International Offshore and Polar Engineering Conference, Vancouver, Canada 59-64

CSIRO [online] (2022) Wave Energy Atlas for Australia. http://awavea.csiro.au/[Accessed 18 Nov 2022]

Dallman AN, Neary VS (n.d.) Characterization of U.S. Wave Energy Converter (WEC) Test Sites: A Catalogue of Met-Ocean Data 2nd Edition (Part 2)

Dalton GJ, Alcorn R, Lewis T (2010) Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America. Renewable Energy 35(2): 443-455. https://doi.org/10.1016/j.renene.2009.07.003

Don Ross (1995) Power of the Waves. Oxford University Press. New York, USA: Oxford University Press

Das Neves Guerreiro R, Chandare S (2010) Caracterización del recurso undimotriz en el litoral marítimo Argentino. In: Congreso y Exhibición Mundial de Ingeniería. Buenos Aires

Emmanouil G, Galanis G, Kalogeri C, Zodiatis G, Kallos G (2016) 10-year high resolution study of wind, sea waves and wave energy assessment in the Greek offshore areas. Renewable Energy 90: 399-419. https://doi.org/10.1016/j.renene.2016.01.031

ESBI [online] (2005) Accessible Wave Energy Resource Atlas: Ireland. https://www.marine.ie/sites/default/files/MIFiles/Docs/General/waveatlas.pdf [Accessed 16 Nov 2022]

Fairley I, Lewis M, Robertson B, Hemer M, Masters I, Horrillo-Caraballo J, Karunarathna H, Reeve DE (2020) A classification system for global wave energy resources based on multivariate clustering. Applied Energy 262. https://doi.org/10.1016/j.apenergy.2020.114515

Fairley I, Smith HCM, Robertson B, Abusara M, Masters I (2017) Spatio-temporal variation in wave power and implications for electricity supply. Renewable Energy 114: 154-165. https://doi.org/10.1016/j.renene.2017.03.075

Fang Y, Wu H, Zhou Q, Jiang B, Wang X (2022) A detailed investigation into the wave energy resource at a small-scale ocean energy test site in China. Frontiers in Energy Research 10. https://doi.org/10.3389/fenrg.2022.883553

Fernández Prieto L, Rodríguez Rodríguez G, Schallenberg Rodríguez J (2019) Wave energy to power a desalination plant in the north of Gran Canaria Island: Wave resource, socioeconomic and environmental assessment. Journal of Environmental Management 231(November 2017): 546-551. https://doi.org/10.1016/j.jenvman.2018.10.071

Ferrari F, Besio G, Cassola F, Mazzino A (2020) Optimized wind and wave energy resource assessment and offshore exploitability in the Mediterranean Sea. Energy 190: 116447. https://doi.org/10.1016/j.jenvman.2018.10.071

Folley M, Cornett A, Holmes B, Liria P, Lenee-Bluhm P (2012) Standardising resource assessment for wave energy converters. 4th International Conference on Ocean Energy 1-7

Gallutia D, Tahmasbi Fard M, Gutierrez Soto M, He JB (2022) Recent advances in wave energy conversion systems: From wave theory to devices and control strategies. Ocean Engineering 252. https://doi.org/10.1016/j.oceaneng.2022.111105

García Medina G, Yang Z, Li N, Cheung KF, Lutu-McMoore E (2023) Wave climate and energy resources in American Samoa from a 42-year high-resolution hindcast. Renewable Energy 210: 604-617. https://doi.org/10.1016/j.renene.2023.03.031

Gaslikova L, Weisse R (2006) Estimating near-shore wave statistics from regional hindcasts using downscaling techniques. Ocean Dynamics 56(1): 26-35. https://doi.org/10.1007/s10236-005-0041-2

Gaudin C, Lowe R, Draper S, Hansen J, Wolgamot H, O'Loughlin C, Fievez J, Taylor D, Pichard A (2018) A Wave Energy Research Centre in Albany, Australia. In: Proceedings of the 4th Asian Wave and Tidal Energy Conference (AWTEC 2018). Taipei. https://tethys-engineering.pnnl.gov/sites/default/files/publications/AWTEC2018-371.pdf

Gleizon P, Campuzano F, Carracedo P, Martinez A, Goggins J, Atan R, Nash S (2017) Wave Energy Resources Along the European Atlantic Coast. In: Marine Renewable Energy 37-69. https://doi.org/10.1007/978-3-319-53536-4_2

Goddijn-Murphy L, Míguez BM, McIlvenny J, Gleizon P (2015) Wave energy resource assessment with AltiKa satellite altimetry: A case study at a wave energy site. Geophysical Research Letters 42(13): 5452-5459. https://doi.org/10.1002/2015GL064490

Goharnejad H, Nikaein E, Perrie W (2021) Assessment of wave energy in the Persian Gulf: An evaluation of the impacts of climate change. Oceanologia 63(1): 27-39. https://doi.org/10.1016/j.oceano.2020.09.004

Gonçalves M, Guedes Soares C (2021) Assessment of the wave energy resource in the Azores coastal area. In: Developments in Renewable Energies Offshore 26-33

Gonçalves M, Martinho P, Guedes Soares C (2014a) Wave energy conditions in the western French coast. Renewable Energy 62: 155-163. https://doi.org/10.1016/j.renene.2013.06.028

Gonçalves M, Martinho P, Guedes Soares C (2014b) Assessment of wave energy in the Canary Islands. Renewable Energy 68: 774-784

Gonçalves M, Martinho P, Guedes Soares C (2018) A 33-year hindcast on wave energy assessment in the western French coast. Energy 165: 790-801. https://doi.org/10.1016/j.renene.2014.03.017

Gonçalves M, Martinho P, Guedes Soares C (2020) Wave energy assessment based on a 33-year hindcast for the Canary Islands. Renewable Energy 152: 259-269. https://doi.org/10.1016/j.renene.2014.03.017

Gorr-Pozzi E, García-Nava H, Larrañaga M, Jaramillo-Torres MG, Verduzco-Zapata MG (2021) Wave energy resource harnessing assessment in a subtropical coastal region of the Pacific. Journal of Marine Science and Engineering 9(11): 1264. https://doi.org/10.3390/jmse9111264

Guedes Soares C (2008) Hindcast of dynamic processes of the ocean and coastal areas of Europe. Coastal Engineering 55(11): 825-826

Guedes Soares C, Bhattacharjee J, Tello M, Pietra L (2013). Review and classification of wave energy converters. Maritime Engineering and Technology 585-594

Guedes Soares C, Weisse R, Carretero JC, Alvarez E (2002) A 40 years hindcast of wind, sea level and waves in European waters. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering-OMAE 2(June): 669-675

Guillou N, Chapalain G (2020) Assessment of wave power variability and exploitation with a long-term hindcast database. Renewable Energy 154: 1272-1282. https://doi.org/10.1016/j.renene.2020.03.076

Guillou N, Lavidas G, Chapalain G (2020) Wave energy resource assessment for exploitation-A review. Journal of Marine Science and Engineering 8(9). https://doi.org/10.3390/jmse8090705

Gunn K, Stock-Williams C (2012) Quantifying the global wave power resource. Renewable Energy 44: 296-304. https://doi.org/10.1016/j.renene.2012.01.101

Guo B, Ringwood JV (2021) A review of wave energy technology from a research and commercial perspective. IET Renewable Power Generation. https://doi.org/10.1049/rpg2.12302

Hemer MA, Katzfey J, Trenham CE (2013) Global dynamical projections of surface ocean wave climate for a future high greenhouse gas emission scenario. Ocean Modelling 70: 221-245. https://doi.org/10.1016/j.ocemod.2012.09.008

Henfridsson U, Neimane V, Strand K, Kapper R, Bernhoff H, Danielsson O, Leijon M, Sundberg J, Thorburn K, Ericsson E, Bergman K (2007) Wave energy potential in the Baltic Sea and the Danish part of the North Sea, with reflections on the Skagerrak. Renewable Energy 32(12): 2069-2084. https://doi.org/10.1016/j.renene.2006.10.006

Hidromod (2020) MARENDATA [online]. marendata. eu [Accessed 18 Dec 2021]

Hogben N, Dacunha NM, O.GF (1986) Global wave statistics. British Maritime Technology, London

Hughes MG, Heap AD (2010) National-scale wave energy resource assessment for Australia. Renewable Energy 35(8): 1783-1791. https://doi.org/10.1016/j.renene.2009.11.001

Ibarra-Berastegi G, Sáenz J, Ulazia A, Serras P, Esnaola G, Garcia-Soto C (2018) Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014-2016). Ocean Engineering 147: 20-29. https://doi.org/10.1016/j.oceaneng.2017.10.018

Ibarra-Berastegi G, Ulazia A, Sáenz J, Serras P, González Rojí SJ, Esnaola G, Iglesias G (2021) The power flow and the wave energy flux at an operational wave farm: Findings from Mutriku, Bay of Biscay. Ocean Engineering 227(April): 1-17. https://doi.org/10.1016/j.oceaneng.2021.108654

IEA-OES (2021) An International Evaluation and Guidance Framework for Ocean Energy Technology

IEA-OES (2023) Annual Report: An Overview of Ocean Energy Activities in 2022

IEG (2019) The test site for MRE in Galicia

Iglesias G, Carballo R (2010) Wave power for La Isla Bonita. Energy 35(12): 5013-5021. https://doi.org/10.1016/j.energy.2010. 08.020

Iglesias G, Carballo R (2011) Wave resource in El Hierro-an island towards energy self-sufficiency. Renewable Energy 36(2): 689-698. https://doi.org/10.1016/j.renene.2010.08.021

Inman DL, Brush BM (1973) The coastal challenge. Science (New York, N. Y.) 181(4094): 20-32. https://doi.org/10.1126/science.181.4094.20

International Waters (2020) KRISO-WETS [online]. https://www.internationalwaters.info/kriso-wets-korea-research-institute-of-ships-ocean-engineering-wave-energy-test-site [Accessed 27 Feb 2024]

IRENA (2020) Innovation outlook: ocean energy technologies

IRENA (2021) Offshore renewables: an action agenda for deployment

IRENA (2023) Renewable Power Generation Costs in 2022

Isaacs JD, Seymour RJ (1973) The ocean as a power resource. International Journal of Environmental Studies 4(1-4): 201-205. https://doi.org/10.1080/00207237308709563

Jadidoleslam N, Özger M, Ağıralioğlu N (2016) Wave power potential assessment of Aegean Sea with an integrated 15-year data. Renewable Energy 86: 1045-1059. https://doi.org/10.1016/j.renene.2015.09.022

Joensen B, Niclasen BA, Bingham HB (2021) Wave power assessment in Faroese waters using an oceanic to nearshore scale spectral wave model. Energy 235. https://doi.org/10.1016/j.energy.2021.121404

Kamranzad B, Amarouche K, Akpinar A (2022) Linking the long-term variability in global wave energy to swell climate and redefining suitable coasts for energy exploitation. Scientific Reports 12(1). https://doi.org/10.1038/s41598-022-18935-w

Kamranzad B, Chegini V, Etemad-Shahidi A (2016a) Temporal-spatial variation of wave energy and nearshore hotspots in the Gulf of Oman based on locally generated wind waves. Renewable Energy 94: 341-352. https://doi.org/10.1016/j.renene.2016.03.084

Kamranzad B, Etemad-Shahidi A, Chegini V (2016b) Sustainability of wave energy resources in southern Caspian Sea. Energy 97: 549-559. https://doi.org/10.1016/j.energy.2015.11.063

Kamranzad B, Hadadpour S (2020) A multi-criteria approach for selection of wave energy converter/location. Energy 204: 117924. https://doi.org/10.1016/j.energy.2020.117924

Kamranzad B, Lin P (2020) Sustainability of wave energy resources in the South China Sea based on five decades of changing climate. Energy 210. https://doi.org/10.1016/j.energy.2020.118604

Kim G, Lee ME, Lee KS, Park JS, Jeong WM, Kang SK, Soh JG, Kim H (2012) An overview of ocean renewable energy resources in Korea. Renewable and Sustainable Energy Reviews 16(4): 2278-2288. https://doi.org/10.1016/j.rser.2012.01.040

Kinsman B (1965) Wind waves, their generation and propagation on the ocean surface. New Jersey: Prentice-Hall

Kozyrakis GV, Spanoudaki K, Varouchakis EA (2023) Long-term wave energy potential estimation in the Aegean and Ionian seas using dynamic downscaling and wave modelling techniques. Applied Ocean Research (131): 103446. https://doi.org/10.1016/j.apor.2022.103446

Krogstad HE, Barstow FS (1999) Satellite wave measurements for coastal engineering applications. Coastal Engineering 37(3-4): 283-307. https://doi.org/10.1016/S0378-3839(99)00030-7

Lavidas G, Kamranzad B (2021) Assessment of wave power stability and classification with two global datasets. International Journal of Sustainable Energy 40(6): 514-529. https://doi.org/10.1080/14786451.2020.1821027

Lavidas G, Polinder H (2019) North Sea wave database (NSWD) and the need for reliable resource data: A 38-year database for metocean and wave energy assessments. Atmosphere 10(9): 1-27. https://doi.org/10.3390/atmos10090551

Lavidas G, Venugopal V (2017a) A 35-year high-resolution wave atlas for nearshore energy production and economics at the Aegean Sea. Renewable Energy 103: 401-417. https://doi.org/10.1016/j.renene.2016.11.055

Lavidas G, Venugopal V (2017b) Wave energy resource evaluation and characterisation for the Libyan Sea. International Journal of Marine Energy 18: 1-14. https://doi.org/10.1016/j.ijome.2017.03.001

Lavidas G, Venugopal V (2018a) Application of numerical wave models at European coastlines: A review. Renewable and Sustainable Energy Reviews 92: 489-500. https://doi.org/10.1016/j.rser.2018.04.112

Lavidas G, Venugopal V (2018b) Prospects and applicability of wave energy for South Africa. International Journal of Sustainable Energy 37(3): 230-248. https://doi.org/10.1080/14786451.2016.1254216

Lavidas G, Venugopal V (2018c) Prospects and applicability of wave energy for South Africa. International Journal of Sustainable Energy 37(3): 230-248. https://doi.org/10.1080/14786451.2016.1254216

Law-Chune S, Aouf L, Dalphinet A, Levier B, Drillet Y, Drevillon M (2021) WAVERYS: a CMEMS global wave reanalysis during the altimetry period. Ocean Dynamics 71(3): 357-378. https://doi.org/

10.1007/s10236-020-01433-w
Leijon M, Boström C, Danielsson O, Gustafsson S, Haikonen K, Langhamer O, Strömstedt E, Stålberg M, Sundberg J, Svensson O, Tyrberg S, Waters R (2008) Wave energy from the North Sea: Experiences from the lysekil research site. Surveys in Geophysics 29(3): 221-240. https://doi.org/10.1007/s10712-008-9047-x
Liberti L, Carillo A, Sannino G (2013) Wave energy resource assessment in the Mediterranean, the Italian perspective. Renewable Energy 50: 938-949. https://doi.org/10.1016/j.renene.2012.08.023
Lira-Loarca A, Cáceres-Euse A, De-Leo F, Besio G (2022) Wave modelling with unstructured mesh for hindcast, forecast and wave hazard applications in the Mediterranean Sea. Applied Ocean Research 122: 103118. https://doi.org/10.1016/j.apor.2022.103118
Liu J, Meucci A, Liu Q, Babanin A V, Ierodiaconou D, Xu X, Young IR (2023) A high-resolution wave energy assessment of south-east Australia based on a 40-year hindcast. Renewable Energy 215. https://doi.org/10.1016/j.renene.2023.118943
López I, Andreu J, Ceballos S, Martínez De Alegría I, Kortabarria I (2013) Review of wave energy technologies and the necessary power-equipment. Renewable and Sustainable Energy Reviews 27: 413-434. https://doi.org/10.1016/j.rser.2013.07.009
Losada IJ, Mendez FJ, Vidal C, Camus P, Izaguirre C (2010) Spatial and temporal variability of nearshore wave energy resources along Spain: Methodology and results. In: MTS/IEEE Seattle, OCEANS 2010: 1-8. https://doi.org/10.1109/OCEANS.2010.5664315
Lucero F, Catalán PA, Ossandón Á, Beyá J, Puelma A, Zamorano L (2017) Wave energy assessment in the central-south coast of Chile. Renewable Energy 114: 120-131. https://doi.org/10.1016/j.renene.2017.03.076
Magagna D, Margheritini L, Alessi A, Bannon E, Boelman E, Bould D, Coy V, de Marchi E, Frigaard P, Guedes Soares C, Golightly C, Hals Todalshaug J, Heward M, Hofmann M, Holmes B, Johnstone C, Kamizuru Y, Lewis T, Macadre LM, Maisondieu C, Martini M, Moro A, Nielsen K, Reis V, Robertson S, Schild P, Soede M, Taylor N, Viola I, Wallet N, Wadbled X, Yeats B (2018) Workshop on identification of future emerging technologies in the ocean energy sector. European Commission
Magagna D, Uihlein A (2015) Ocean energy development in Europe: Current status and future perspectives. International Journal of Marine Energy 11: 84-104. https://doi.org/10.1016/j.ijome.2015.05.001
Martinez A, Iglesias G (2020) Wave exploitability index and wave resource classification. Renewable and Sustainable Energy Reviews 134(July): 110393. https://doi.org/10.1016/j.rser.2020.110393
Masuda Y (1986) An experience of wave power generator through tests and improvement. In: D. v Evans and A.F.O. de Falcão, eds. Hydrodynamics of Ocean Wave-Energy Utilization. Berlin, Heidelberg: Springer Berlin Heidelberg 445-452
Mattarolo G, Lafon F, Benoit M (2009) Wave energy resource off the French coasts: the ANEMOC database applied to the energy yield evaluation of Wave Energy Converters. In: 8th European Wave and Tidal Energy 247-255
May-Varas N, Robertson B (2020) Global Wave Energy Testing Sites. Seafloor Bathymetry and Slope. https://ir.library.oregonstate.edu/concern/technical_reports/2n49t811b
Mazzaretto OM, Lucero F, Besio G, Cienfuegos R (2020) Perspectives for harnessing the energetic persistent high swells reaching the coast of Chile. Renewable Energy 159: 494-505. https://doi.org/10.1016/j.renene.2020.05.031
Mckenzie C, Stephen K, Xin Z, Wagner M, Wainwright D (2010) Windmills in Antarctica
META [online] (2022) Wales's National Test Facility. https://www.meta.wales/ [Accessed 16 Nov 2022]
Monárdez P, Acuña H, Scott D (2008) Evaluation of the potential of wave energy in Chile. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE 801-809
Monteforte M, lo Re C, Ferreri GB (2015) Wave energy assessment in Sicily (Italy). Renewable Energy 78: 276-287. https://doi.org/10.1016/j.renene.2015.01.006
MORE-EST [online] (2022) http://www.morenergylab.polito.it/more-est-platform/ [Accessed 4 Nov 2022]
Morim J, Cartwright N, Etemad-Shahidi A, Strauss D, Hemer M (2014) A review of wave energy estimates for nearshore shelf waters off Australia. International Journal of Marine Energy 7: 55-70. https://doi.org/10.1016/j.ijome.2014.09.002
Morim J, Cartwright N, Hemer M, Etemad-Shahidi A, Strauss D (2019) Inter- and intra-annual variability of potential power production from wave energy converters. Energy 169: 1224-1241. https://doi.org/10.1016/j.energy.2018.12.080
Mørk G, Barstow S, Kabuth A, Pontes MT (2010) Assessing the global wave energy potential. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering-OMAE 3(June 2010): 447-454
Mouakkir L, el Hou M, Mordane S, Chagdali M (2022) Wave energy potential analysis in the Casablanca-Mohammedia coastal area (Morocco). Journal of Marine Science and Application 21(1): 92-101. https://doi.org/10.1007/s11804-022-00261-2
Neary VS, Ahn S (2023) Global atlas of extreme significant wave heights and relative risk ratios. Renewable Energy 208: 130-140. https://doi.org/10.1016/j.renene.2023.03.079
Neill SP, Lewis MJ, Hashemi MR, Slater E, Lawrence J, Spall SA (2014) Inter-annual and inter-seasonal variability of the Orkney wave power resource. Applied Energy 132: 339-348. https://doi.org/10.1016/j.apenergy.2014.07.023
Neill SP, Vögler A, Goward-Brown AJ, Baston S, Lewis MJ, Gillibrand PA, Waldman S, Woolf DK (2017) The wave and tidal resource of Scotland. Renewable Energy 114(A): 3-17. https://doi.org/10.1016/j.renene.2017.03.027
NREL (2022) Marine Energy Atlas [online]. https://maps.nrel.gov/marine-energy-atlas/[Accessed 4 Nov 2022]
Ocean Plug [online] (2021) https://tethys.pnnl.gov/project-sites/ocean-plug-portuguese-pilot-zone [Accessed 24 Dec 2021]
O'Connell R, de Montera L, Peters JL, Horion S (2020) An updated assessment of Ireland's wave energy resource using satellite data assimilation and a revised wave period ratio. Renewable Energy 160: 1431-1444. https://doi.org/10.1016/j.renene.2020.07.029
O'Connell R, Kamidelivand M, Furlong R, Guerrini M, Cullinane M, Murphy J (2024) An advanced geospatial assessment of the Levelised cost of energy (LCOE) for wave farms in Irish and western UK waters. Renewable Energy 221. https://doi.org/10.1016/j.renene.2023.119864
OES-IEA (2021) Annual Report: An Overview of Ocean Energy Activities in 2020
OSU (n. d.) Oregon State University. PacWave South Wave Energy Test Site. Testing wave energy for the future
OSU (n. d.) Oregon State University. PacWave North Wave Energy Test Site. Testing wave energy for the future
Our World in Data (2023) Levelized cost of energy by technology,

World [online]. https://ourworldindata.org/grapher/levelized-cost-of-energy [Accessed 26 Dec 2023]

Panicker NN (1976) Power resource estimate of ocean surface waves. Ocean Engineering 3(6): 429-439. https://doi.org/10.1016/0029-8018(76)90016-0

Patel RP, Nagababu G, Arun Kumar SVV, Seemanth M, Kachhwaha SS (2020) Wave resource assessment and wave energy exploitation along the Indian coast. Ocean Engineering 217: 107834. https://doi.org/10.1016/j.oceaneng.2020.107834

Patel RP, Nagababu G, Kachhwaha SS, Surisetty VVAK, Seemanth M (2022) Techno-economic analysis of wave energy resource for India. Journal of the Indian Society of Remote Sensing. https://doi.org/10.1007/s12524-022-01538-3

Pelamis Wave Power (2011) The Farr Point Wave Farm Development-Environmental

Penalba M, Ulazia A, Saénz J, Ringwood JV (2020) Impact of long-term resource variations on wave energy Farms: The Icelandic case. Energy 192. https://doi.org/10.1016/j.energy.2019.116609

Pilar P, Guedes Soares C, Carretero JC (2008) 44-year wave hindcast for the North East Atlantic European coast. Coastal Engineering 55(11): 861-871. https://doi.org/10.1016/j.coastaleng.2008.02.027

Ponce de León S, Orfila A, Simarro G (2016) Wave energy in the Balearic Sea. Evolution from a 29-year spectral wave hindcast. Renewable Energy 85: 1192-1200. https://doi.org/10.1016/j.renene.2015.07.076

Pontes MT, Athanassoulis GA, Barstow S, Bertotti L, Cavaleri L, Holmes B (1998) The European wave energy resource. In: Proceedings of the 3rd European Wave Energy Conference. Patras, Greece

Pontes MT, Aguiar R, Pires HO (2005) A nearshore wave energy atlas for Portugal. Journal of Offshore Mechanics and Arctic Engineering 127(3): 249-255. https://doi.org/10.1115/1.1951779

Pontes MT, Athanassoulis GA, Barstow S, Cavaleri L, Holmes B, Mollison D, Oliveira-Pires H (1996) An atlas of the wave energy resource in Europe. Journal of Offshore Mechanics and Arctic Engineering 118(4): 307-309. https://doi.org/10.1115/1.2833921

Pourali M, Kavianpour MR, Kamranzad B, Alizadeh MJ (2023) Future variability of wave energy in the Gulf of Oman using a high resolution CMIP6 climate model. Energy 262. https://doi.org/10.1016/j.energy.2022.125552

Qiu S, Liu K, Wang D, Ye J, Liang F (2019) A comprehensive review of ocean wave energy research and development in China. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2019.109271

Quayle R, Changery M (1981) Estimates of coastal deepwater wave energy potential for the world. In: OCEANS 81: 903-907

Ramos S, Díaz H, Guedes Soares C, Lavidas G (2020) Identifying compatible locations for wave energy exploration with different wave energy devices in Madeira Islands. In: C. Guedes Soares, ed. Developments in Renewable Energies Offshore. London: Taylor & Francis Group 111-122

Ramos S, Gonçalves M, Guedes Soares C (2021) A method for identifying compatible locations for wave energy exploration with different WECS. In: Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering 1-10. https://doi.org/10.1115/OMAE2021-62949

Ramos-Marin S, Guedes Soares C (2024) Overview of the wave energy resources in Europe by regional seas and countries. In: C. Guedes Soares & T. A. Santos, eds. Advances in Maritime Technology and Engineering. London: Taylor & Francis Group 659-670. https://doi.org/10.1201/9781003508779-72

Rascle N, Ardhuin F (2013) A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization. Ocean Modelling 70(October): 174-188. https://doi.org/10.1016/j.ocemod.2012.12.001

Ratsimandresy AW, Sotillo MG, Carretero Albiach JC, Álvarez Fanjul E, Hajji H (2008) A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project. Coastal Engineering 55(11): 827-842. https://doi.org/10.1016/j.coastaleng.2008.02.025

Reeve DE, Chen Y, Pan S, Magar V, Simmonds DJ, Zacharioudaki A (2011) An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK. Renewable Energy 36(9): 2404-2413. https://doi.org/10.1016/j.renene.2011.02.020

Reguero BG, Losada IJ, Méndez FJ (2015) A global wave power resource and its seasonal, interannual and long-term variability. Applied Energy 148: 366-380. https://doi.org/10.1016/j.apenergy.2015.03.114

Reguero BG, Menéndez M, Méndez FJ, Mínguez R, Losada IJ (2012) A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. Coastal Engineering 65: 38-55. https://doi.org/10.1016/j.coastaleng.2012.03.003

Reguero BG, Vidal C, Menéndez M, Méndez FJ, Mínguez R, Losada I (2011) Evaluation of global wave energy resource. OCEANS 2011 IEEE-Spain

Ribal A, Babanin AV, Zieger S, Liu Q (2020) A high-resolution wave energy resource assessment of Indonesia. Renewable Energy 160: 1349-1363. https://doi.org/10.1016/j.renene.2020.06.017

Ribeiro AS, deCastro M, Rusu L, Bernardino M, Dias JM, Gomez-Gesteira M (2020) Evaluating the future efficiency of wave energy converters along the NW Coast of the Iberian Peninsula. Energies 13(14): 3563. https://doi.org/10.3390/en13143563

Ringwood J, Brandle G (2015) A new world map for wave power with a focus on variability. In: Proceedings of the 11th European Wave and Tidal Energy Conference. Nantes, France

Robertson B, Hiles C, Luczko E, Buckham B (2016) Quantifying wave power and wave energy converter array production potential. International Journal of Marine Energy 14: 143-160. https://doi.org/10.1016/j.ijome.2015.10.001

Rodríguez GR, Cabrera L, Pacheco M (2015) Assessing and modeling annual patterns in wave energy resources off Canary archipelago. Renewable Energies Offshore-1st International Conference on Renewable Energies Offshore, RENEW 2014

Rusu E (2014) Evaluation of the wave energy conversion efficiency in various coastal environments. Energies 7(6): 4002-4018. https://doi.org/10.3390/en7064002

Rusu E (2018) Study of the Wave Energy Propagation Patterns in the Western Black Sea. Applied Sciences (Switzerland) 8(6). https://doi.org/10.3390/app8060993

Rusu E, Guedes Soares C (2009) Numerical modelling to estimate the spatial distribution of the wave energy in the Portuguese nearshore. Renewable Energy 34(6): 1501-1516. https://doi.org/10.1016/j.renene.2008.10.027

Rusu E, Guedes Soares C (2012a) Wave energy pattern around the Madeira Islands. Energy 45(1): 771-785. https://doi.org/10.1016/j.energy.2012.07.013

Rusu E, Onea F (2013) Evaluation of the wind and wave energy along the Caspian Sea. Energy 50(1): 1-14. https://doi.org/10.1016/j.energy.2012.11.044

Rusu E, Onea F (2019) An assessment of the wind and wave power potential in the island environment. Energy 175: 830-846. https://doi.org/10.1016/j.energy.2019.03.130

Rusu L, Guedes Soares C (2012b) Wave energy assessments in the

Azores islands. Renewable Energy 45: 183-196. https://doi.org/10.1016/j.renene.2012.02.027

Rusu L, Onea F (2017) The performance of some state-of-the-art wave energy converters in locations with the worldwide highest wave power. Renewable and Sustainable Energy Reviews 75 (May 2016): 1348-1362. https://doi.org/10.1016/j.rser.2016.11.123

Rusu L, Pilar P, Guedes Soares C (2008) Hindcast of the wave conditions along the west Iberian coast. Coastal Engineering 55(11): 906-919. https://doi.org/10.1016/j.coastaleng.2008.02.029

Rusu L, Rusu E (2021) Evaluation of the worldwide wave energy distribution based on ERA5 data and altimeter measurements. Energies 14(2). https://doi.org/10.3390/en14020394

Sa Cotrim C, Semedo A, Lemos G (2022) Brazil wave climate from a high-resolution wave Hindcast. Climate 10(4). https://doi.org/10.3390/cli10040053

Safewave project [online] (2021) WESE Project. https://www.safewave-project.eu/wese-project/ [Accessed 18 Dec 2021]

Saket A, Etemad-Shahidi A (2012) Wave energy potential along the northern coasts of the Gulf of Oman, Iran. Renewable Energy 40(1): 90-97. https://doi.org/10.1016/j.renene.2011.09.024

Sanil Kumar V, Anoop TR (2015) Wave energy resource assessment for the Indian shelf seas. Renewable Energy 76: 212-219. https://doi.org/10.1016/j.renene.2014.11.034

Sannasiraj SA, Sundar V (2016) Assessment of wave energy potential and its harvesting approach along the Indian coast. Renewable Energy 99: 398-409. https://doi.org/10.1016/j.renene.2016.07.017

Sasaki W (2017) Predictability of global offshore wind and wave power. International Journal of Marine Energy 17: 98-109. https://doi.org/10.1016/j.ijome.2017.01.003

Serras P, Ibarra-Berastegi G, Sáenz J, Ulazia A (2019). Combining random forests and physics-based models to forecast the electricity generated by ocean waves: A case study of the Mutriku wave farm. Ocean Engineering 189. https://doi.org/10.1016/j.oceaneng.2019.106314

Shadman M, Roldan-Carvajal M, Pierart FG, Haim PA, Alonso R, Silva C, Osorio AF, Almonacid N, Carreras G, Maali Amiri M, Arango-Aramburo S, Rosas MA, Pelissero M, Tula R, Estefen SF, Pastor ML, Saavedr, OR (2023) A Review of Offshore Renewable Energy in South America: Current Status and Future Perspectives. Sustainability (Switzerland). https://doi.org/10.3390/su15021740

Shadman M, Silva C, Faller D, Wu Z, de Freitas Assad LP, Landau L, Levi C, Estefen SF (2019) Ocean renewable energy potential, technology, and deployments: A case study of Brazil. Energies 12(19). https://doi.org/10.3390/en12193658

Sierra JP, Martín C, Mösso C, Mestres M, Jebbad R (2016) Wave energy potential along the Atlantic coast of Morocco. Journal of Marine Science and Engineering 11(11): 2159. https://doi.org/10.3390/jmse11112159

Sierra JP, Mösso C, González-Marco D (2014) Wave energy resource assessment in Menorca (Spain). Renewable Energy 71: 51-60. https://doi.org/10.1016/j.renene.2014.05.017

Sierra JP, Martín C, Mösso C, Mestres M, Jebbad R (2016) Wave energy potential along the Atlantic coast of Morocco 96(A): 20-32. https://doi.org/10.1016/j.renene.2016.04.071

Silva D, Bento AR, Martinho P, Guedes Soares C (2015) High resolution local wave energy modelling in the Iberian Peninsula. Energy 91: 1099-1112. https://doi.org/10.1016/j.energy.2015.08.067

Silva D, Martinho P, Guedes Soares C (2018) Wave energy distribution along the Portuguese continental coast based on a thirty-three years hindcast. Renewable Energy 127: 1064-1075. https://doi.org/10.1016/j.renene.2018.05.037

Silva D, Rusu E, Guedes Soares C (2013) Evaluation of various technologies for wave energy conversion in the Portuguese nearshore. Energies 6(3): 1344-1364. https://doi.org/10.3390/en6031344

Simonetti I, Cappietti L (2023) Mediterranean coastal wave-climate long-term trend in climate change scenarios and effects on the optimal sizing of OWC wave energy converters. Coastal Engineering 179: 104247. https://doi.org/10.1016/j.coastaleng.2022.104247

Slow Mill (2024) Texel Pilot [online]. https://slowmill. nl/Market/Texel-Pilot/ [Accessed 27 Feb 2024]

Smith HCM, Haverson D, Smith GH (2013) A wave energy resource assessment case study: Review, analysis and lessons learnt. Renewable Energy 60: 510-521. https://doi.org/10.1016/j.renene.2013.05.017

Smith HCM, Maisondieu C (2014) Resource Assessment for Cornwall, Isles of Scilly and PNMI

Soomere T, Eelsalu M (2014) On the wave energy potential along the eastern Baltic Sea coast. Renewable Energy 71: 221-233. https://doi.org/10.1016/j.renene.2014.05.025

Sotillo MG, Ratsimandresy AW, Carretero JC, Bentamy A, Valero F, González-Rouco F (2005) A high-resolution 44-year atmospheric hindcast for the Mediterranean Basin: Contribution to the regional improvement of global reanalysis. Climate Dynamics 25(2-3): 219-236. https://doi.org/10.1007/s00382-005-0030-7

Soukissian TH, Denaxa D, Karathanasi F, Prospathopoulos A, Sarantakos K, Iona A, Georgantas K, Mavrakos S (2017) Marine renewable energy in the Mediterranean Sea: Status and perspectives. Energies 10(10): 1-56. https://doi.org/10.3390/en10101512

SOWFIA (2011) SOWFIA Deliverable D 2.1: Catalogue of Wave Energy Test Centres

Sterl A, Caires S (2005) Climatology, variability and extrema of ocean waves: the Webbased KNMI/ERA40 wave atlas. International Journal of Climatology 25: 963-977

Sterl A, Komen GJ, Cotton PD (1998) Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather forecasts reanalysis: Validating the reanalyzed winds and assessing the wave climate. Journal of geophysical research 103(C3): 5477-5492. https://doi.org/10.1029/97JC03431

Stopa JE, Cheung KF, Tolman HL, Chawla A (2013) Patterns and cycles in the Climate Forecast System Reanalysis wind and wave data. Ocean Modelling 70: 207-220. https://doi.org/10.1016/j.ocemod.2012.10.005

Tethys (2022a) Tethys Map Viewer [online]. https://tethys.pnnl.gov/map-viewer-marine-energy? f% 5B0%5D=technology% 3A429&f%5B1%5D=type%3Aproject_site_annex_iv [Accessed 14 Nov 2022]

Tethys Engineering (2023) MRE Photo Library [online]. https://tethys-engineering.pnnl.gov/photo-library [Accessed 26 Dec 2023]

Thomaz TB, Crooks D, Medina-Lopez E, van Velzen L, Jeffrey H, Mendia JL, Arias RR, Minguela PR (2019) O&M models for ocean energy converters: Calibrating through real sea data. Energies 12(13). https://doi.org/10.3390/en12132475

Uihlein A, Magagna D (2016) Wave and tidal current energy-A review of the current state of research beyond technology. Renewable and Sustainable Energy Reviews 58: 1070-1081. https://doi.org/10.1016/j.rser.2015.12.284

van Nieuwkoop JCC, Smith HCM, Smith GH, Johanning L (2013) Wave resource assessment along the Cornish coast (UK) from a 23-year hindcast dataset validated against buoy measurements.

Renewable Energy 58: 1-14. https://doi.org/10.1016/j.renene.2013.02.033

Venugopal V, Nemalidinne R (2015) Wave resource assessment for Scottish waters using a large scale North Atlantic spectral wave model. Renewable Energy 76: 503-525. https://doi.org/10.1016/j.renene.2014.11.056

Vijaykumar N, Gault J, Devoy R, Dunne D, Mahony CO (2004) Computational Modeling of Environmental Processes: A Hindcast of Wind Atlas over Irish Waters. Computing, 3-8

Wan Y, Zhang J, Meng J, Wang J (2015) A wave energy resource assessment in the China's seas based on multi-satellite merged radar altimeter data. Acta Oceanologica Sinica 34(3): 115-124. https://doi.org/10.1007/s13131-015-0627-6

Wang CN, Nhieu NL (2023) Integrated DEA and hybrid ordinal priority approach for multi-criteria wave energy locating: a case study of South Africa. Soft Computing 27(24): 18869-18883. https://doi.org/10.1007/s00500-023-09043-6

Wang S, Yuan P, Li D, Jiao Y (2011) An overview of ocean renewable energy in China. Renewable and Sustainable Energy Reviews

WaveRoller [online] (2021) Waveroller. https://aw-energy.com/waveroller/[Accessed 24 Dec 2021]

Webb A, Waseda T, Kiyomatsu K (2020) A high-resolution, long-term wave resource assessment of Japan with wave–current effects. Renewable Energy 161: 1341-1358. https://doi.org/10.1016/j.renene.2020.05.030

Weisse R, Günther H (2007) Wave climate and long-term changes for the Southern North Sea obtained from a high-resolution hindcast 1958-2002. Ocean Dynamics 57(3): 161-172. https://doi.org/10.1007/s10236-006-0094-x

Weisse R, Weisse R, Günther H, Feser F (2002) A 40-year high-resolution wind and wave hindcast for the Southern North Sea, (May) 97-104

West BA, Gagnon IF, Wosnik M (2016) Tidal Energy Resource Assessment for McMurdo Station, Antarctica. https://apps.dtic.mil/sti/pdfs/AD1025148.pdf

World Energy Council (UK) (1993) Renewable energy resources: Opportunities and constraints 1990-2020. United Kingdom: World Energy Council

Yaakob O, Hashim FE, Mohd Omar K, Md Din AH, Koh KK (2016) Satellite-based wave data and wave energy resource assessment for South China Sea. Renewable Energy 88: 359-371. https://doi.org/10.1016/j.renene.2015.11.039

Zodiatis G, Galanis G, Nikolaidis A, Kalogeri C, Hayes D, Georgiou GC, Chu PC, Kallos G (2014) Wave energy potential in the Eastern Mediterranean Levantine Basin. An integrated 10-year study. Renewable Energy 69: 311-323. https://doi.org/10.1016/j.renene.2014.03.051