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Techno-economic assessment of global and regional wave energy resource potentials and profiles in hourly resolution

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HIGHLIGHTS

- Global-local wave power potential is estimated.
- Economic potential estimation is presented with projection until 2050.
- Point absorbers have a wide operating range leading to high yields and low costs.
- Wave power is a feasible alternative for power supply in coastal regions and islands.
- Energy systems can benefit from the complementarity of wave power and solar PV.

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ABSTRACT

Climate change is driving the adoption of sustainable energy, with low-cost solar photovoltaics and wind power at the forefront. However, land-constrained regions and islands have a limited onshore renewable energy potential. Wave power may prove useful for such regions, supported by growing literature in the field. This study delves into wave power's techno-economic potential, addressing a gap in previous assessments focused solely on theoretical or technical prospects. Utilising hourly wave data and a wave energy converter manufacturer's power matrix, global wave electricity yield is estimated. Considering projected costs, levelised cost of electricity is used to gauge economic viability. Although wave power is currently expensive, the results suggest that it could become cost-competitive with offshore wind power in the 2030s, with levelised cost of electricity below 70 €/MWh by 2035 in areas with good wave energy resources. Finally, the paper contributes openly accessible, hourly capacity factor data of global wave power generation, empowering further energy system modelling research. This study paves the way for informed decision-making on wave power's role in a diversified, sustainable energy future.

1. Introduction

The adverse effect of fossil fuels consumption on the global climate has led to increasing concerns about the utilisation of these resources to satisfy the energy demand. Climate change, caused by massive anthropogenic greenhouse gas emissions, is one of the most significant threats the modern society has ever faced [1]. To reduce greenhouse gas emissions, the utilisation of fossil fuels must be minimised, the role of renewable energy (RE) resources in the energy supply must increase, and, ultimately, renewables must substitute fossil fuels in the energy supply [2,3]. While hydropower is still the most prevalent RE resource, solar photovoltaic (PV) systems and onshore wind turbines represent most new capacity installations in many regions of the world in recent years [4,5].

1.1. Renewable energy deployment

The speed of new RE capacities installation must increase in the near

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Abbreviations: CAPEX, Capital Expenditures; CF, Capacity Factor; ECWAM, European Centre for Medium-Range Weather Ocean Wave Model; EEZ, Exclusive Economic Zone; F-2BH, Floating 2 Body Heave; FLH, Full Load Hours; H_s, Significant Wave Height; LCOE, Levelised Cost of Electricity; MFWAM, Météo-France Wave Model; OPEX, Operational Expenditures; PV, Photovoltaics; T_p, Peak Wave Period; VRE, Variable Renewable Energy; WEC, Wave Energy Converter.

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future, as the defossilisation of the heat, transport, and industry sectors will lead to the fast growth of electricity demand [3,6]. Solar PV and onshore wind have the potential to become the main energy sources for future energy systems in all regions of the world. However, other RE technologies will be part of the mix to support flexibility and reliability of the system [3] and to supply energy where and when solar PV and wind resources are limited due to high population density or other constraints. In recent years, ocean energy has emerged as an untapped and potentially valuable RE resource [7]. One of the reasons is that the cost of ocean energy technologies is becoming more economically attractive. The capital expenditures (CAPEX) of these technologies are expected to further decrease in the years to come, leading to economically attractive levelised cost of electricity (LCOE). Compared to other variable RE technologies (VRE), ocean resources deliver a less variable generation profile and relatively high capacity factors. Additionally, these resources produce power close to coastal populations where energy demand is concentrated [8]. This stable generation profile positions ocean energy as a key player in future energy grids, potentially reducing the need for large-scale energy storage solutions [9]. Furthermore, ocean energy may have higher social acceptance than land-based VRE options since the introduction of these technologies will not interfere with existing land-use patterns [10].

Various technologies have been developed in recent years to harvest energy from the ocean [7,11]. Among these, established and rapidly expanding renewable sources include offshore wind turbines [12,13] and offshore floating solar PV systems [9,14]. However, wave energy converters (WEC) [11,15–17] are gaining significant attention. Primarily, it is due to their much higher potential, for example, compared to tidal energy [18,19], which requires specific geographical conditions. Additionally, WECs offer greater technological maturity compared nascent technologies like salinity gradient [20,21], and ocean thermal energy conversion [22,23], which also have specific requirements. Focusing specifically on wave energy converters (WECs) among various ocean energy technologies, this paper explores their potential as a key player in future energy systems.

1.2. Wave energy converters

Technologies related to WEC are yet to converge and some are below relative technical maturity, i.e., the technology readiness level is not higher than six with only experimental tests in controlled environments [24], but significant progress is expected in the upcoming years. CAPEX of WECs is expected to decrease substantially. Based on the cost development of low-carbon energy technologies [27], the CAPEX of WECs can be reduced below 2000 €/kW by 2050.

Since the technology of wave energy harvesting has not converged, different methods and devices have been proposed to extract wave power according to geographical conditions, deployment depth, and changes in wave behaviour in different places, resulting in various companies working in this field. The European Marine Energy Centre presents a comprehensive list of wave developer companies and devices [25]. Although there are numerous types of WECs, these WECs can be categorised into four main groups based on their design principle: point absorbers [26], attenuators [27], oscillating water columns [11], oscillatory surge converters [11,15], and overtopping devices [11].

Point absorbers can extract energy in all wave directions by converting wave energy to electricity through the relative motion between a body that moves in response to wave motion and fixed structures. Since these relatively small devices are usually fixed directly to the ocean floor, they are typically deployed in intermediate waters [26]. Examples of this WEC type are the CorPower device [28] and Powerbuoy [29], developed by Ocean Power Technology.

Attenuators, also known as linear absorbers, are long structures of a series of floating sections linked together via flexible joints that allow each section to swing relative to others. These snake-like WECs are oriented in parallel with wave direction. In this device, the power unit is placed between sections and the wave-induced motion of each section of the device is utilised to generate electricity. One of the well-known devices of this type was the Pelamis WEC developed by Pelamis Wave Power [27].

Oscillating water columns utilise the energy from the movement of waves to create air pressure difference within a chamber. This pressure is then directed through an air turbine. By connecting the turbine to a rotary generator, electricity can be generated. These devices are mostly integrated in breakwaters [30,31], with Mutriku [32] having almost 10 years of operation. However, there are concepts suitable for deeper waters away from the shore [11].

Overtopping devices are long structures designed to enable the waves to fill a reservoir, elevating the water level above that of the adjacent ocean. The elevated water generates a pressure differential between the water in the reservoir and the water at the surface, which propels the fluid through a low-head turbine linked to a generator, thus creating electricity in a way that resembles conventional hydropower. These devices can be situated either on land or afloat in deeper waters away from the shore [11].

Oscillatory surge converters: Commonly, these WECs are fixed to the seabed and their main operation is in the pitch mode, utilising the transformation of the wave resource into surge. These devices can have different sizes, but their power take-off most commonly is hydraulic rams driving a linear generator. These devices are most suitable for shallow water regions [11,15].

1.3. Literature review

The literature on wave energy research has been growing since the 1970s, and in recent years, due to the development of the technology, the impending threat of climate change and the need for diversified solutions for the energy transition. This nascent field is still in the phase of investigating the most optimal configuration of WECs [15,16,33], in contrast to other RE sources, where crystalline silicon PV and horizontal axis three-blade wind turbines are standard in solar and wind power. Several substantial commercial attempts have halted so far, such as Wavebob and Pelamis [34,35] and the New Entrants Reserve (NER300), where WECs were allocated 141 m€ but most did not proceed to materialisation [36]. Even though these hurdles slow down the development, others are marching forward, such as CorPower, which has already had successful dry and ocean tests and several generations of WECs [37].

Besides the technology specific investigations, there are studies examining the wave energy at various scales. Such wave energy resource assessments can be divided into global, large basins and specific locations/regions.

Ocean wave energy has a high potential according to Reguero et al. [38], who estimated the global offshore wave power potential at 32,000 TWh/yr, basing their numbers on the findings of Mørk et al. [39], which is reduced to 16,000 TWh/yr when considering the direction of waves. A general review of renewable electricity generation potentials performed by Beaumelle et al. [40] shows that the technical potential of wave energy found in literature ranges between 500 TWh and 17,500 TWh. Ulazia et al. [41] evaluated the global performance of WECs with a dataset produced by WAM from 1900 to 2010, identifying that indeed wave energy production can differ per region and decade investigated, on average up to 20%. Several authors analysed the global wave energy flux, with datasets findings that wave energy variations can be significantly different and with large variations per dataset, indicating that global models have clear limitations [42–45].

Some examples of regionally focused wave energy assessments include the land-constrained Maldives [9,46], an island off the coast of Alaska [47], Europe [48], Scotland [49], North Sea [50], Mediterranean [51–53], South Africa [54], and others [55–57]. Some studies investigate the integration of wave power into the local energy system [9] by researching the interplay of wave power with other sources of energy such as solar PV, wind power, bioenergy, and diesel generators. A study for Mediterranean [51] examines the optimal sizing of WECs for local conditions and suggests that "one-size fits all" does not work for wave power. Dialyna and Tsoutsos [52] assess the performance of WECs deployed in the Mediterranean region and conclude that although the performance is good the cost barrier must be addressed with further research and development. Friedrich et al. [58] evaluated the performance of multi-generation systems in the Mediterranean and the Scottish Islands and revealed that with the inclusion of wave power, demand side management strategies can reduce CO_2 emission by 21%, cost by 8%, and the necessity for energy storage up to 40–45%. Such characteristics were predominately attributed to the different temporal generation profiles of wave power, which can act as a counterbalance to high variability. Despite the limited area of small islands and the often very good wave energy resources, the inclusion of wave power in energy system analyses for islands is not yet standard [59].

Some studies have reviewed the state of the wave energy research [11,17,60,61]. Lavidas [62] highlights three key factors for success in wave energy projects: resource (indicated by the energy content of the wave crest), extractable energy (dependent on WEC characteristics and power matrix), and economics (determined by investment and operational expenditures). Falcão [11] looks at the history of wave energy research and presents a review of the hydrodynamics, wave energy capturing technologies, power equipment, and moorings. The common thread among the review articles is the lack of standardisation, limited understanding of wave energy resources, unknowns regarding the economic performance, the durability and reliability, and grid integration [25]. An evaluation of global wave energy resource was done by Reguero et al. [38] and their study initially explored the temporal variations in global wave resources across different time scales, ranging from months to decades. Subsequently, they provided a preliminary calculation of the wave energy that could be harnessed along coastlines. It is important to note that this estimation was purely theoretical and did not take into account energy conversion technology or cost considerations. Gunn and Stock-Williams [63] assessed the worldwide wave energy potential by utilising data with a resolution of 30 arc minutes (0.5°) and a 3-h interval, along with the Pelamis WEC. Their analysis assumed a 30 nautical mile area available for the deployment of wave farms, leading to an estimated global theoretical wave power resource of 2.11 ± 0.05 TW. This assessment did not consider cost-related factors. A comprehensive assessment of the wave energy potential was done by Weiss et al. [64], who investigated the potential zones of available wave and offshore wind energy resources, structural survivability of the energy converters, logistical barriers for installations, such as the availability of ports, and distance to consumption centres in high spatial and temporal resolution. However, Weiss et al. [64] did not assess the economic potential of wave power and the respective possible cost of electricity generation from wave power; thus, such an investigation remains as a research gap in the field of wave energy research. Furthermore, there is a lack of available studies that provide open access to data on hourly wave power profiles. These data are crucial for assessing the integration of wave power into energy system analyses.

This study aims to contribute to the understanding of wave energy resources considering the cost of wave power generation. While some studies have assessed the theoretical and technical potential of wave energy on a global scale [38,63], the novelty of this study is in the estimation of the techno-economic potential of global wave energy resources. The significant wave height and peak wave period are considered for each hour of a year in 0.45° spatial resolution and converted to wave electricity yield applying the power matrix from a leading WEC manufacturer. The capital and operational expenditures projections for WECs are used to calculate the LCOE to estimate the economic potential. The culminating objective of the study is the resulting hourly capacity factors data of global wave electricity generation that are openly available for further research in energy system modelling.

This paper is structured as follows: first, it introduces the concept of wave power and discusses previous research as well as areas that require further investigation. Then, the methods and data utilised in the study are described. Next, the article presents findings related to the theoretical, technical, and economic potentials of wave power. After that, the authors offer their interpretation of the results and acknowledge the study's limitations in the discussion section. Finally, the conclusions are drawn.

2. Methods and data

2.1. Wave power modelling

Wave power modelling was performed for the case of a single WEC unit to calculate hourly and annual electricity output based on given wave resources data. For the technical and economic potential assessment, the individual WEC units' performance data was augmented by assumptions on wave farm dimensioning and reduction of individual WEC efficiency due to wave shading.

2.1.1. Capacity factor and full load hour for single units

For each location, the hourly capacity factor, CF, was calculated with the power matrix of the WEC using hourly data for significant wave height, H_s, and peak wave period, T_p, as described in Eq. 1:

$$CF = \frac{PM(T_p, H_s)}{P_{peak}} \tag{1}$$

where P_{peak} is a rated capacity of the device and PM is the power matrix of the WEC. The sum of the hourly capacity factors within a year represents the ideal full load hours for a WEC unit without consideration of the availability factor.

2.1.2. Cost calculation

The operational cost (OPEX) of the WEC is low compared to the CAPEX, which finally represent a major part of the WEC LCOE. The main part of the CAPEX in wave energy projects is related to the mechanical and electrical structure of the WEC, which is independent of water depth and shore distance. The rest of the CAPEX includes the foundation of WEC, installation, grid connection, and mooring system, which are dependent on the project location at the sea.

The CAPEX per unit of power was calculated using the reported base CAPEX numbers by CorPower [65] and adjusted to the installation depth and distance from shore. Since the technology is on early maturity stage and data on deployment cost in different regions is not available, a uniform CAPEX was assumed across all countries. OPEX were calculated as the share of CAPEX, inheriting the depth and distance to shore adjustments. CAPEX and OPEX projections assume a volume-driven cost reduction as known for modular technical systems, which is within the range of independent assumptions [66]. The deeper and farther installation sites can negatively impact the costs due to increased complexity in installation of mooring lines, grid connections, and labour needed both for initial setup and ongoing maintenance. Table 1 shows the

Table 1
Financial and technical assumptions for the point absorber WEC. Assumptions are based on [65].

Year	CAPEX	Opex	Lifetime	Availability	Depth Factor	Distance Factor
Units	[€/kW]	[%]	[Years]	[%]	[€/kW/m]	[€/kW/km]
2020	21,420	4.9%	20	65%	0.86	3.42
2025	6326	5.8%	20	84%	0.66	2.97
2030	2777	2.7%	25	93%	0.66	2.97
2035	2247	2.5%	25	95%	0.46	2.52
2040	2012	2.4%	30	95%	0.46	2.52
2045	1819	2.5%	30	95%	0.36	2.14
2050	1731	2.4%	30	95%	0.36	2.14

financial and technical assumptions used for estimating the CAPEX in the Eq. 2.

$$CAPEX = CAPEX_{base} + F_D \cdot D + F_d \cdot d \tag{2}$$

$$CAPEX = CAPEX_{base}, D \leq 10km \ AND \ d \leq 50m$$

where d is sea depth, D is distance to the shore, F_d is the sea depth factor in €/kW/m, and F_D is the distance factor in €/kW/km. The factors, OPEX and other financial and technical assumptions were obtained from the WEC manufacturer.

For all locations that are at most 50 m deep and 10 km far, the CAPEX is equal to the base CAPEX.

The LCOE was calculated using the Eqs. 3–5:

$$LCOE = \frac{CAPEX \cdot crf + OPEX}{FLh_{farm} \cdot AvF_{unit}} \tag{3}$$

$$FLh_{farm} = FLh_{unit} \cdot \eta_{farm} \tag{4}$$

$$crf = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \tag{5}$$

Where *crf* is the capital recovery factor, FLh_{farm} is the full load hours of the WEC farm, FLh_{unit} is the full load hours of an individual WEC unit of the wave power farm, AvF_{unit} is availability factor of the WEC units, η_{farm} is the efficiency of the wave farm considering effects of wave shading on the individual units. The availability factor reflects the uptime of the wave power farm, considering maintenance and unexpected events that may occur during the ramp-up phase in the initial years of operation. Capital recovery factor (*crf)* is a function of weighted average cost of capital (WACC), and the lifetime, *N*, of the WEC as shown in Eq. 5. WACC was set at 7%.

2.2. Electricity potential calculation

The technical wave power potential was calculated for each individual country's Exclusive Economic Zone (EEZ) in 0.45° resolution. This involved calculating the total installable capacity within each EEZ by multiplying the area of each grid square by the WEC installation density. The resolution is equivalent to 50 km by 50 km at the equator, or 35 km by 50 km at mid latitudes. The annual electricity production potential was calculated using the Eq. 6:

$$AEP = Area \cdot InstallationDensity \cdot FLh_{unit} \cdot AvF_{unit} \cdot \eta_{farm} \tag{6}$$

where FLh_{unit} is the full load hours of a WEC unit, AvF_{unit} is availability factor of the WEC units, within the wave power farm, and η_{farm} is the efficiency of the wave power farm considering effects of wave shading on the individual units. Following the reasoning of Taminiau and van der Zwaan [67], limited area of EEZ was allowed to be used for WEC installation as a maximum theoretical potential. Taminiau and van der Zwaan analysed the usage patterns within the highly utilised EEZ of the Netherlands and argued that, conservatively, 25% of the EEZ can be used for offshore wind turbines. Considering the similarity in installation and farm layouts of offshore wind turbines and WECs, it follows that 25% can also be allocated to WECs. However, WECs have stricter depth requirements and denser farm layouts that could hinder shared use of maritime space. Therefore, a more conservative 15% EEZ area limitation was adopted for this study.

Following the theoretical potential, the impractical and restricted areas were filtered out to calculate the technical potential according to the following criteria:

- depth up to 1000 m;
- distance to shore up to 300 km;
- exclusion of all protected areas;
- sea ice concentration up to 15%.

Finally, the economic potential for one WEC was extracted from the technical potential, limiting the LCOE to certain thresholds as presented in section 3.

The wave power profiles were calculated taking the weighted average capacity factors of the best sites within each region's EEZ. The best 20% of sites were given a weight of 0.3, the following 10% were given a weight of 0.2, and the following 20% were given a weight of 0.1. The bottom 50% of sites were not considered. The weighing was done following the approach described in Bogdanov and Breyer [68]. The best sites were defined as the sites with highest average capacity factor in a year.

2.3. Data inputs and resources

To assess the wave energy resources, global significant wave height and peak wave period data were used to estimate the theoretical wave energy potential. The technical potential was derived from the theoretical potential, considering the sea depth and distance to the coast limits, protected areas, and areas covered with ice. Following the technical potential, the economic potential was estimated by determining the LCOE at each site and filtering out the sites that do not fit within cost thresholds.

2.3.1. Different wave models and related data

Significant wave height and peak wave period data are available from the following sources:

1. European Centre for Medium-Range Weather Ocean Wave Model (ECWAM) [69]
2. Météo-France Wave Model (MFWAM) from EC Copernicus Marine Service [70]
3. WAVEWATCH III from National Oceanic and Atmospheric Administration [71]

The data from MFWAM were not chosen because the underlying calculations were undergirded by the ECWAM model. WAVEWATCH III and ECWAM model have very similar features, but WAVEWATCH III was developed by the US National Oceanic and Atmospheric Administration with higher attention on model verification in the seas of North America. ECWAM was developed by the European Centre for Medium-Range Weather Forecasts and this model results are better validated in the European seas. Considering the importance of ocean energy for densely populated European counties, the ECWAM data was chosen for this study.

The data selected for this study exclusively pertains to the weather year 2005, considering dependence of wave energy on wind energy and in alignment with the rationale outlined in [72], as the total full load hours of the year 2005 closely matched the average full load hours of the decade. Employing data from the same year allows for the consideration of variations and interplay within weather dynamics and their effect on energy systems. Inter-annual variations of the wave energy potential are out of scope of this study.

2.3.2. Wave energy converters

Technical data, specifically the power matrices and installation densities, were obtained for three core WECs, namely the point absorber by CorPower [73], the attenuator by Pelamis [74], and a generic floating 2 body heaving (F-2BH) [74]. While the Pelamis concept and F-2BH were discussed in the past, they faced difficulties with further development. The point absorber technology of CorPower, however, is currently in active deployment. CAPEX, efficiency, installation density and actual technology provider future development projections could be retrieved only for the point absorber technology of CorPower. Thus, the CorPower technology was used for the wave power economic potential assessment. The used method can be replicated for all WECs applying respective financial assumptions.

a. CorPower

CorPower's WEC [73] is of point absorber type, a buoy-like device connected to the seabed by a tensioned mooring line. The technology from CorPower is capable of oscillating in resonance with the incoming waves, amplifying the wave motion and power capture. The system is also capable of detuning in relation to waves, increasing its survivability in storms by creating transparency to the incoming wave energy. Conversely, the device's dimensions and configuration make it inoperable in conditions of low sea states when the waters are calm. The device is designed for depth from 30 m and deeper, with an economic sweet spot between 30 and 100 m, and deeper installations are also possible with projections down to 1000 m. The mooring system is designed to handle up to 7 m of tidal variation. The power matrix of CorPower's WEC with a nominal capacity of 400 kW is displayed in Fig. 1.

CorPower WECs are designed to be operated in tandem within a farm of 10–30 MW, where the electricity is collected from the array into a central hub, as shown in Fig. 2. The array's shape is elongated, and the array is placed perpendicular to the prominent wave direction. The spacing allows for an installation density of 14.79 MW/km^2. The array interaction effects are typically grid losses and auxiliary consumption, totalling 9.2% and is expected to drop to 9.1% by 2040. The availability is assumed to be at 65% in 2020 and is expected to grow steadily to 95% by 2040 and is dependent on WEC maintenance shutdowns, storm protection, etc.

b. Pelamis

The Pelamis technology was developed by Pelamis Wave Power. The WEC consisted of semi-submerged tubes joined on hinges forming a snake-like structure that produces power by harnessing the wave energy to move the adjacent tubes relative to each other. The system was placed facing the incoming waves. The company behind the technology went bankrupt in 2014 [35] stopping further development and deployment of the technology. The power matrix of the Pelamis WEC with a nominal capacity of 750 kW is displayed in Fig. 3.

To calculate the technical potential for the Pelamis WEC, the same 14.79 MW/km^2 installation density was assumed, mirroring the density used for CorPower. This chosen density aligns with figures in literature, tending toward a more conservative estimation [63,75,76].

c. Floating 2 Body Heaving

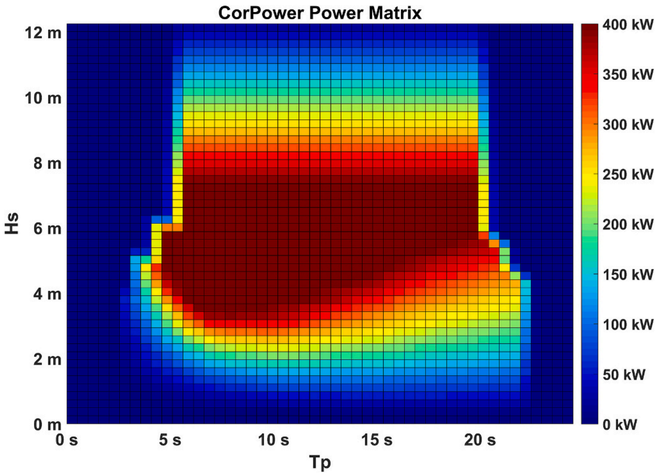

Fig. 1. CorPower's WEC power matrix [73]. Abbreviation: H_s – significant wave height, T_p – peak wave period.

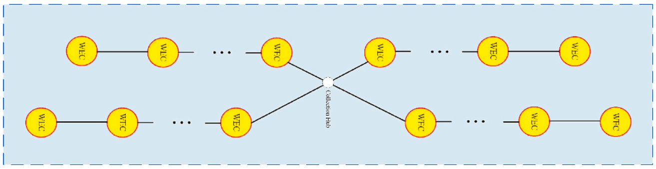

Fig. 2. CorPower proposed WEC farm layout for point absorbers.

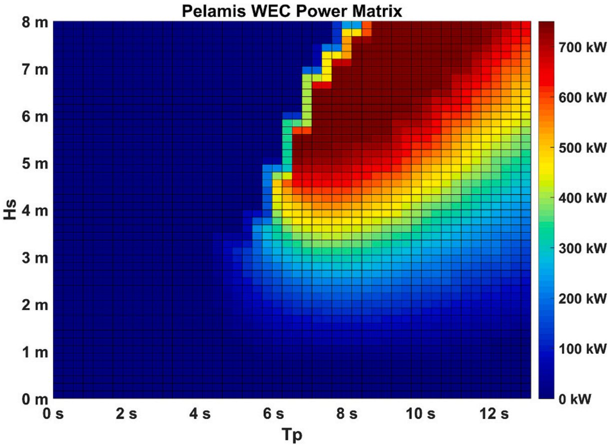

Fig. 3. Pelamis power matrix [74]. Abbreviation: H_s – significant wave height, T_p – peak wave period.

F-2BH converters consist of one submerged section and another floating section, which are connected by a mass-spring-damper system [11]. The relative motion of the two bodies, which is caused by the heaving (bobbing up-and-down) of the floating section, power the electricity generation system. The technology was mainly developed by Wavebob, which went bankrupt in 2013 [34] and no further financial or technical details were found. Fig. 4 depicts the power matrix of a generic 1000 kW F-2BH WEC.

Likewise, the same 14.79 MW/km^2 installation density was assumed for the F-2BH WEC to calculate the technical potential. This density is in line with figures from literature, leaning toward a more conservative estimation [50,77].

2.3.3. Other data sources

To accurately calculate the installation and grid connection costs and filter out the impractical and restricted areas, the following data was used listed in Table 2.

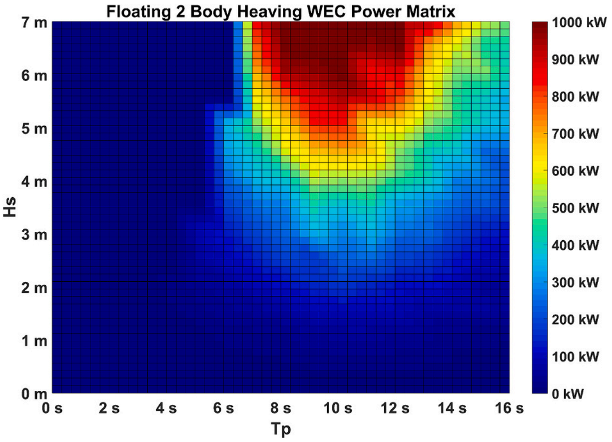

Fig. 4. Floating 2 Body Heaving WEC power matrix [15,74]. Abbreviation: H_s – significant wave height, T_p – peak wave period.

Table 2
Datasets used for installation and grid connection cost estimation and exclusion of practical sites.

Data	Spatial Resolution	Temporal Resolutions	Source
Bathymetry	0.45°	Geologic time scale	[78]
Distance To Shore	0.45°	Geologic time scale	calculated
World Database on Protected Areas	0.45°	–	[79]
Sea Ice Concentration	0.45°	monthly	[80]
Exclusive Economic Zones	vector file	–	[81]

The bathymetry, the topography of the ocean floor, is presented in Fig. 5. The distance to shorelines of the continents and islands was calculated in MATLAB. Sea ice concentration for 2021 was obtained from the NASA National Snow and Ice Data Center [80] and the data for the maximum extent of sea ice in 2021 is presented in Fig. 6. EEZ data, obtained from Flanders Marine Institute [81], was used to estimate the wave power potential for all the investigated regions in the world.

3. Results

The results consist of hourly capacity factors matrix and cost matrices for projected LCOE for different years from 2020 to 2050 in 5-year steps. The following subsections present the geospatial results for wave power full load hours, CAPEX, LCOE, technical, and economic potentials in select regions and wave electricity generation profiles for the same selected regions. Since the Pelamis and F-2BH WEC manufacturers discontinued their activities, their financial projections are not considered. CorPower's point absorber WEC is the only technology that is developed and manufactured, so this technology is picked as central for this study and the CAPEX, LCOE, economic potential are calculated only for the case of this technology.

3.1. *Wave energy full load hours*

Full load hours for a point absorber WEC around the world calculated using ocean weather data for the year 2005 is depicted in Fig. 7 (top). High capacity factors in the North Atlantic present potentially large wave power potentials for Greenland, Iceland, and the Faroe Islands. Similarly, the Pacific islands, southern Chile, South Africa, southern Madagascar, southern Australia, and New Zealand could benefit from this RE source with a capacity factor of 80%. Herein lies the additional benefit of wave energy over solar energy, as the best wave energy sites are generally further away from the equator. Excellent wave power regions can be found in northern and southern latitudes with some distance to the equator. The wind abundant North Sea region can also harness wave power in the range of 3500–4500 FLH. The potential of wave power is limited in the Gulf of Mexico and the Caribbean, the Mediterranean, and the Malay Archipelago with capacity factors below 20%, though such regions could still take advantage of the wave energy resources via optimal sizing of the WECs [51].

The frequency of hours during which the point absorber WEC is unable to generate electricity due to wave conditions falling outside its operational range is depicted in the bottom Fig. 7. This corresponds to the cumulative hours when the significant wave height and peak wave period deviate from the specified operational parameters as defined by the WEC's power matrix. The figure illustrates the extensive range within which this WEC can function effectively, as it aligns well with the wave conditions found in the majority of locations worldwide, with the exception of certain seas and large lakes.

The global FLH values for the other two WECs are depicted in Fig. 8 (top). As shown in the diagrams, the Pelamis and the F-2BH WECs have significantly lower FLHs compared to the point absorber WEC, due to their much narrower band of operation as a function of significant wave height and peak wave period. Practically, no areas close to shores are above 4000 FLH with most area below 2000 FLH or 23% capacity factor. In relative terms, the advantage of the point absorber WEC is even more pronounced, particularly near the equator. Point absorber WEC outperforms other WECs with FLH that are 80% higher in most regions, even near the shorelines.

In addition, the bottom diagrams depicted in Fig. 8 illustrate the periods of inoperability for these two WECs. Significant swaths of the ocean remain outside the effective operational range of the Pelamis WEC for a substantial number of hours each year, with over 7000 h downtime in Mediterranean shorelines, Caribbean Sea, Baltic Sea and elsewhere. Only a slightly improved performance is observed for the F-2BH WEC due to a slightly wider operation band versus Pelamis. While Pelamis FLH devices can generate more power in certain regions compared to F-2BH, they also experience more downtime. This is because Pelamis operates within a wider band at peak power output, while F-2BH has a broader operational range, even if it sacrifices some power generation in specific conditions.

3.2. *Capital expenditures*

The CAPEX values for the point absorber WEC are projected to decline from over 20,000 €/kW in 2020 to 1731 €/kW in 2050, following a volume-driven experience curve. Fig. 9 depicts the CAPEX values calculated according to Eq. 2, with filters applied to show only the

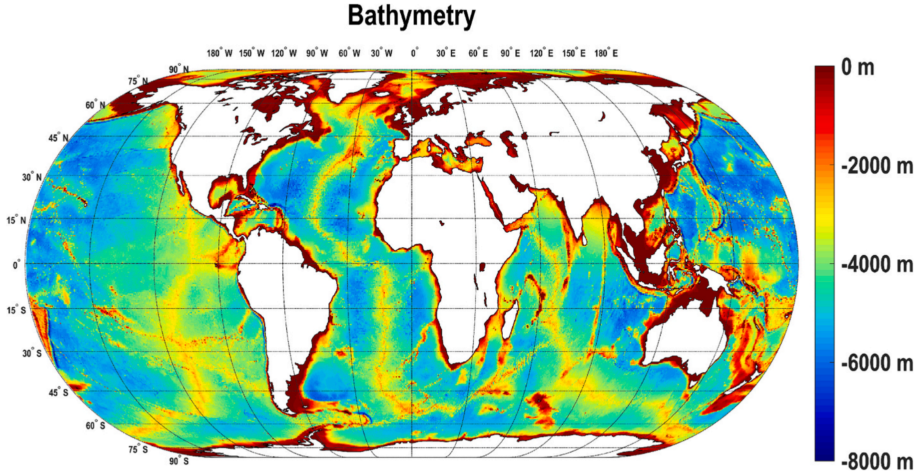

Fig. 5. Global bathymetry data [78].

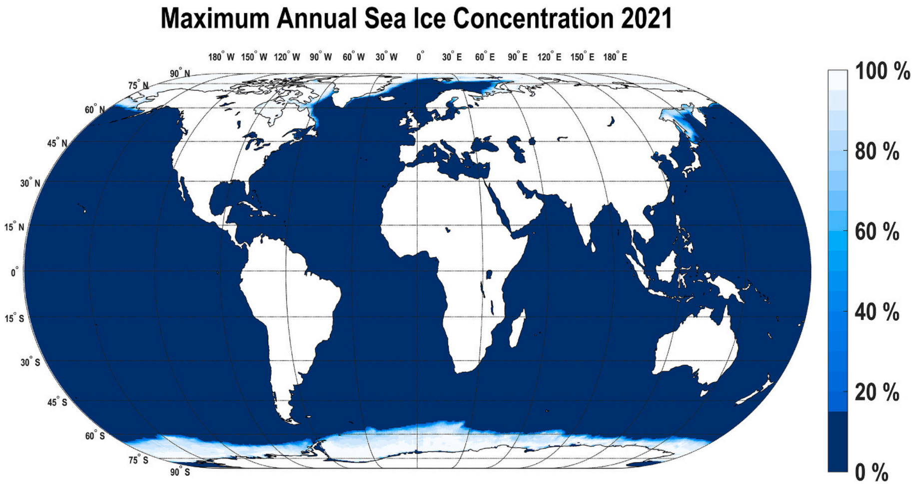

Fig. 6. The maximum annual extent of sea ice concentration in 2021 [80].

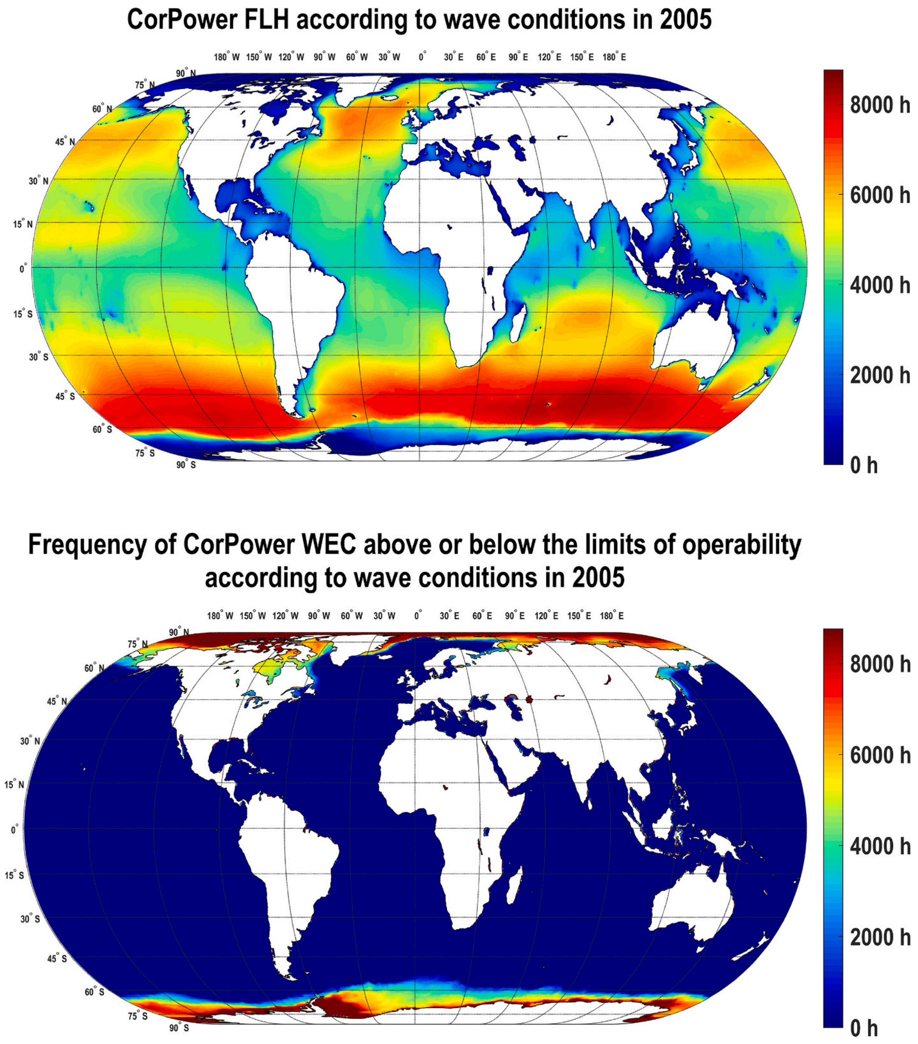

Fig. 7. Global full load hour values for the point absorber WEC (top) and the frequency above or below its limits of operability for the conditions of the weather year 2005 (bottom).

practical and unrestricted regions. As can be seen in Fig. 9, the CAPEX starts rising at farther and deeper sites. For example, in the Malay Archipelago (5°N, 105°E), where the topology is shallow enough to enable installations further from the shore, the CAPEX rises by 30% compared to near-shore areas.

The cumulative capacity of the point absorber WEC that could be installed at specific CAPEX levels is illustrated in Fig. 10. By 2050, over 35 TW of wave power can be installed at a CAPEX level below 2000

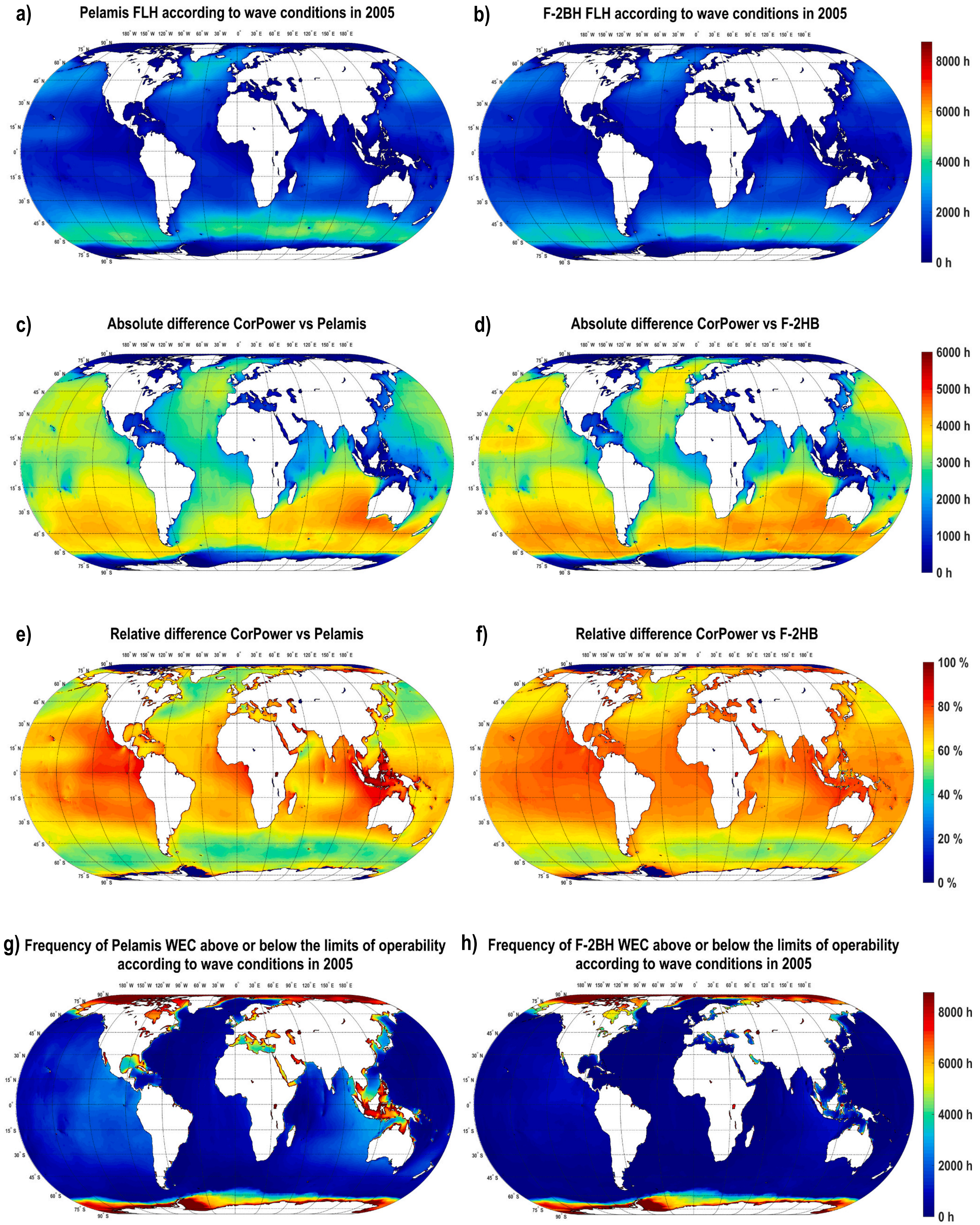

Fig. 8. Global full load hour values for the Pelamis (a) and F-2BH (b) WECs, the difference compared to the point absorber WEC in absolute (c, d) and relative (e, f) terms and the frequency above or below their limits of operability (g, h).

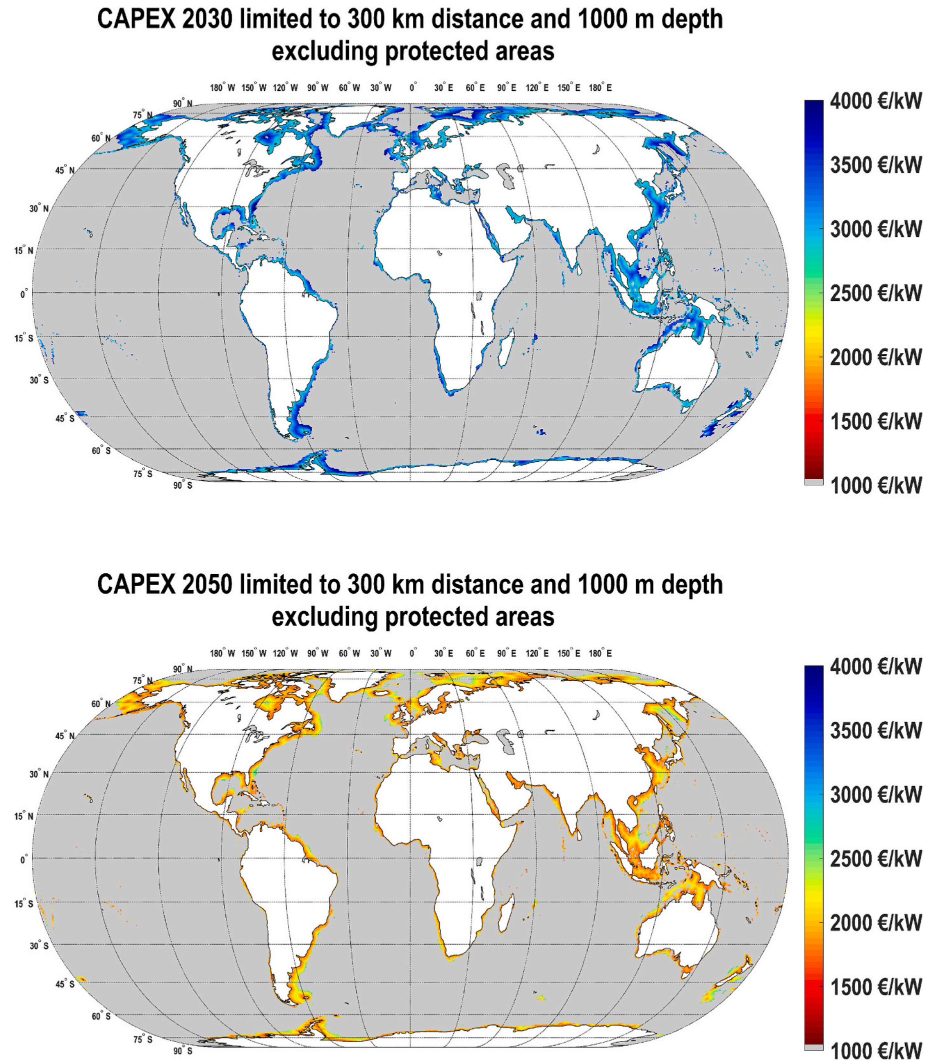

Fig. 9. Global CAPEX values in 2030 and 2050 for point absorber WEC. The map excludes World Protected Areas, areas beyond exclusive economic zones, and regions deeper than 1000 m and where annual sea ice concentration goes above 15%.

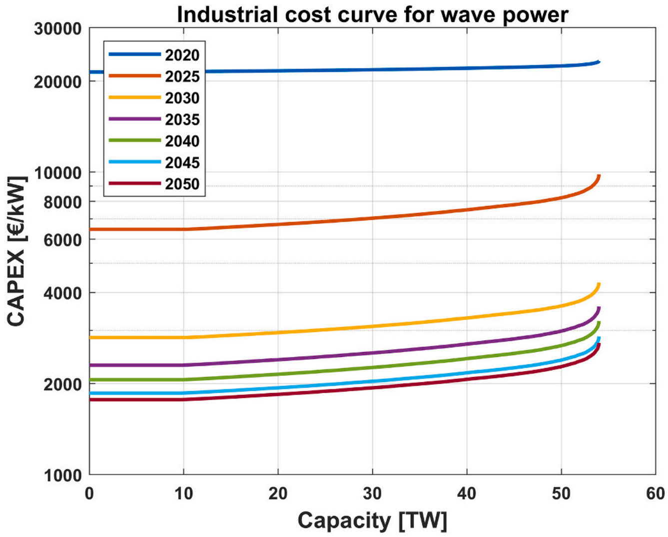

Fig. 10. Industrial cost curve for wave power CAPEX for point absorber WEC, showing the total installable wave power capacity at a particular CAPEX level, i.e., 35 TW can be installed for <2000 €/kW in 2050.

€/kW, and more potential is available at higher CAPEX values. A significant drop is expected in the CAPEX of WECs over the next decade, as a consequence of commercialisation of WECs, industrial scaling and market growth, which is reflected Fig. 10.

3.3. *Levelised cost of electricity*

The LCOE values calculated for the point absorber WEC farms in the areas where WEC installations are technically possible are presented in Fig. 11. The LCOE in 2020 was very costly in all parts of the world, due to the high CAPEX in this nascent industry. By 2030, wave power already shows potential to be cost-competitive, with LCOE below 60 €/MWh in regions with high FLH, such as the northern coast of the British Isles (59°N, 5°W) or the coast off Cape Town in South Africa (35°S, 19°E). By 2050, there is potential for wave power with LCOE below 50 €/MWh, which could make wave power one of the least cost RE sources in regions with high land constraints, in particular islands, such as the Faroe Islands (60°N, 7°W) and the Pacific Islands, including Hawaii (22°N, 160°W). In other regions with less severe area limitations, wave power could further diversify the electricity mix to work in tandem with other RE sources, such as solar PV and onshore wind power, for example in Scotland, Ireland, Portugal, South Africa, southern Australia, New Zealand, or Chile.

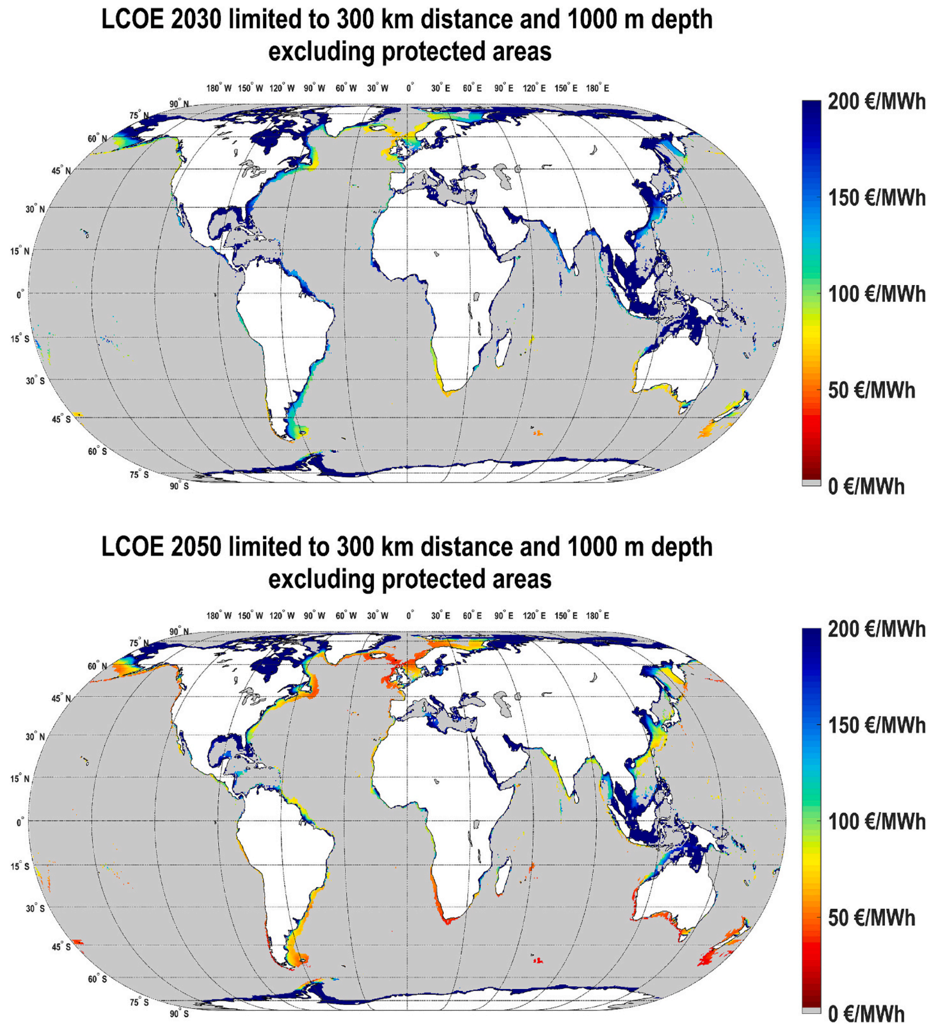

Fig. 11. Global LCOE values for wave power in 2030 and 2050 for point absorber WEC. The map excludes World Protected Areas, areas beyond exclusive economic zones, and regions deeper than 1000 m and where annual sea ice concentration goes above 15%.

3.4. *Technical and economic potential*

The global technical potential for wave power installable capacity reaches >50 TW, considering the practical sites within 300 km of coastlines and filtering out sites with depth over 1000 m, protected areas, and areas with sea ice concertation over 15% at any time within a year. This potential contrasts with the estimates by Gunn and Stock-Williams [63] with 2.11 TW of continued power flows (with correction by FLH one obtains installable capacity) of theoretical power potential and Mørk et al. [39] with 2.98 TW of theoretical power potential of continued flows. The differences in these results are potentially related to the broader area assumptions of this study, whereas Gunn and Stock-Williams assumed only 30 nautical miles (55.6 km) of shorelines as practical sites. Gunn and Stock-Williams estimate the technical potential via the Pelamis WEC to be about 96.6 GW, or 4.6% of the theoretical potential, a much lower value compared to the results of this study, because of the Pelamis WEC's narrower operation band, as evident in Fig. 8, and the restrictive assumptions in theoretical potential calculations. Another estimate of the global theoretical wave power potential is 2 TW of continued flows reported by Pelc and Fujita [82], who base their number on the book by the World Energy Council titled "Renewable energy resources: opportunities and constraints 1990–2020", which could not be obtained.

In 2020, the CorPower WEC exhibits a technical efficiency of 90.8% and an availability of 65%. As a result, the study indicates a potential electricity generation of up to 67,000 TWh. Projections from 2035 onwards, with an efficiency of 90.9% and an availability of 95%, suggest a potential increase to 98,000 TWh for the point absorber WEC. This contrasts with 32,000 TWh by Reguero et al. [38], 18,500 TWh by Gunn and Stock-Williams (assuming baseload operation of 2.11 TW) [63], 17,500 TWh by Pelc and Fujita [82], 26,100 TWh by Mørk et al. [39], and 4400 TWh by Jacobson [83]. The greater technical potential of this study is enabled by a broader and farther resource availability assumption with more accessible area and the more efficient and thus more optimal WEC. Comparatively, the Pelamis WEC indicates a technical electricity generation potential of 23,500 TWh, amounting to a third of the value generated by the point absorber WEC due to its lower energy extraction efficiency. Furthermore, the F-2BH WEC demonstrates an even lower potential at 20,400 TWh, attributed to a narrow operational band evident in its power matrix (Fig. 4). Detailed technical potential numbers in global-local resolution are available in the Supplementary Material S2.

However, not all technical capacity may be economically attractive, as the LCOE of the generated electricity can vary depending on the depth of installations, distance from shore, and local wave conditions. The cost curves of the global economic potential available in different years calculated for point absorber WEC is shown in Fig. 12. By 2035, there is almost 3600 TWh of annual wave electricity available at or below 50 €/MWh. By 2050 the amount of electricity is 29,000 TWh, 9300 TWh, and 2900 TWh for LCOE levels not higher than 50 €/MWh, 40 €/MWh,

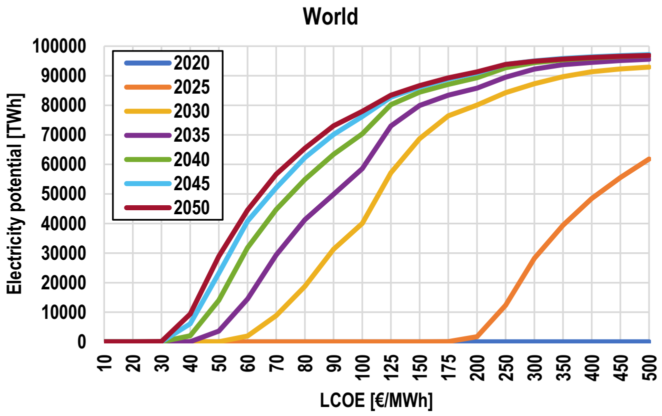

Fig. 12. Cost curves of the global economic potential of wave power for point absorber WEC, showing the total electricity generation potential at a particular LCOE level, i.e., 29,000 TWh can be generated for <50 €/MWh in 2050.

and 35 €/MWh, respectively.

Economic potential cost curves for specific countries and regions around the world with relatively limited land area are presented in Fig. 13. If the rapid cost decline projections for the assumed point absorber come to fruition, the bulk of the technical wave power potential in these countries becomes available for <150 €/MWh by 2035, except for Indonesia, due to its relatively low wave energy resources in the Malay Archipelago; however, most wave power potential remains rather expensive until 2030.

3.5. Wave electricity generation profiles

The wave electricity generation profiles for select regions with relatively limited land area are presented in Fig. 14. The profiles were generated using the weighted average algorithm according to the method described in Section 2.2. This visualisation depicts how wave power production varies within a day (vertical axis) and across different days and seasons (horizontal axis). The presence of straight vertical lines means stable wave power production within a day. Most locations show patterns of seasonality with more electricity generation in winter than summer (flipped at the sites in the southern hemisphere), indicating a potential complementarity of wave power and solar PV. The highest FLH are observed in the British Isles, South Africa, and New Zealand, at 5900 h, 6400 h, and 7100 h, respectively, which can also be observed in Fig. 7.

4. Discussion

Wave energy may present itself as a great alternative to other RE sources, especially in land-constrained island nations or densely populated coastal regions. Regions with a high penetration of VRE sources and access to coastlines rich in wave energy resources can benefit from complementarity and diversity, as a valuable energy system feature [84]. While solar and onshore wind resources can provide low-cost electricity in most regions of the world [3,85], island nations can have limited area for onshore power production capacities due to land use competition with tourism, industry, or agriculture, or due to topology on mountainous islands [59]. Offshore wind power may present itself as the best alternative in such regions with mature technology readiness and well-established manufacturers. However, wave power can emerge from a complementary option to a strong competitor to offshore wind power if the cost projections for WECs become true, as indicated in a recent study for the British Islands [86]. Besides, offshore wind power installations may have technical limitations due to the availability of ships and ports capable of installing and handling large wind turbines [64,87] and some nations limit wind turbines installations due to possible interference with radar systems [88]. The relatively small dimensions of WECs may enable smaller ships to be utilised for the installations of WECs [89]. Additionally, WECs have no known impact on radar systems. Compared to offshore wind turbines, WECs have a higher installation density and a lower visual impact, which means that a smaller area of ocean is needed to generate the same amount of electricity as a large wind farm while being less visually intrusive. Such benefits of wave power may lead to faster permitting processes and thus accelerate ocean energy deployment.

4.1. Economic performance

Currently, almost all technical wave power potential in the world is prohibitively expensive due to high CAPEX and OPEX. With the growing urgency of climate change mitigation, however, the increase in research and development efforts can reduce the costs to enable relevant wave power installations at best sites in the world. Consequently, the increasing capacities will accumulate know-how in the industry, driving further cost reductions as a consequence of the learning curve. The economies of scale and market maturation can decrease the costs even further. LCOE below 100 €/MWh can be achieved by 2030 at best sites, establishing wave power as a feasible choice alongside offshore wind power. Globally, the LCOE of offshore wind power is below 90 €/MWh as of the early 2020s and power delivery contracts below 50 €/MWh are being signed around the world [90]. Such LCOE values can be achieved with wave power at best sites in 2030 and at larger scale by 2035 (see sections 3.3 and 3.4).

4.2. Complementarity and diversification

Besides the economic performance, wave power can provide additional value via the diversification of energy supply, as discussed for several RE sources by Aghahosseini et al. [84]. In most locations, the wave power CF profiles are rather stable, but still show some seasonality. However, variation of the wave power CF profiles is inversely correlated with single-axis tracking solar PV CF profiles [91], as can be seen in Fig. 15. Wave power and solar PV can contribute in a complementary way to supply renewable electricity throughout the year and curb the demand for seasonal energy storage [63,92,93]. Such a complementarity and impact on storage demand was shown by Keiner et al. [9] for the case of the Maldives. While it is unlikely that anything other than solar PV will become the dominant source of electricity in the near future [85], wave power is uniquely suited to complement solar PV in times of lower solar resource availability.

Moreover, while most waves are created by wind, implying a high wave-wind correlation, swell waves can transfer the wind energy from distant seas to the shore as they are fetched over long distances from multiple weather systems, resulting in a natural smoothing effect on the power profile, allowing for wave power to be produced at times of low winds along the coasts [94]. Aside from the solar-wind-wave complementarity, supply diversification can be of high importance for energy security [95] to hedge against the risks of unforeseen disruptions in any one of the industries, although it may be difficult to assign a monetary value to the diversification [84,96]. Moreover, it is possible to install WECs within offshore wind farms [64], presenting a potential for cost savings via shared grid connection and marine spatial planning framework. This offshore wind-wave nexus may enable cost reductions beyond the financial forecasts, opening a possibility for higher economic potential for both technologies. Complementarity of wave power, solar PV, and wind power generation and the impact of wave power on possible energy transition pathways are important topics [9] and requires further assessment in future studies.

Exploitation of solar PV in oceanic conditions will naturally demand the resolving of multiple issues; however, several companies provide competing concept to resolve these challenges [97–100]. These concepts will soon be proven with demonstration projects making the co-location of offshore wave and solar to further reduce offshore RE generation costs

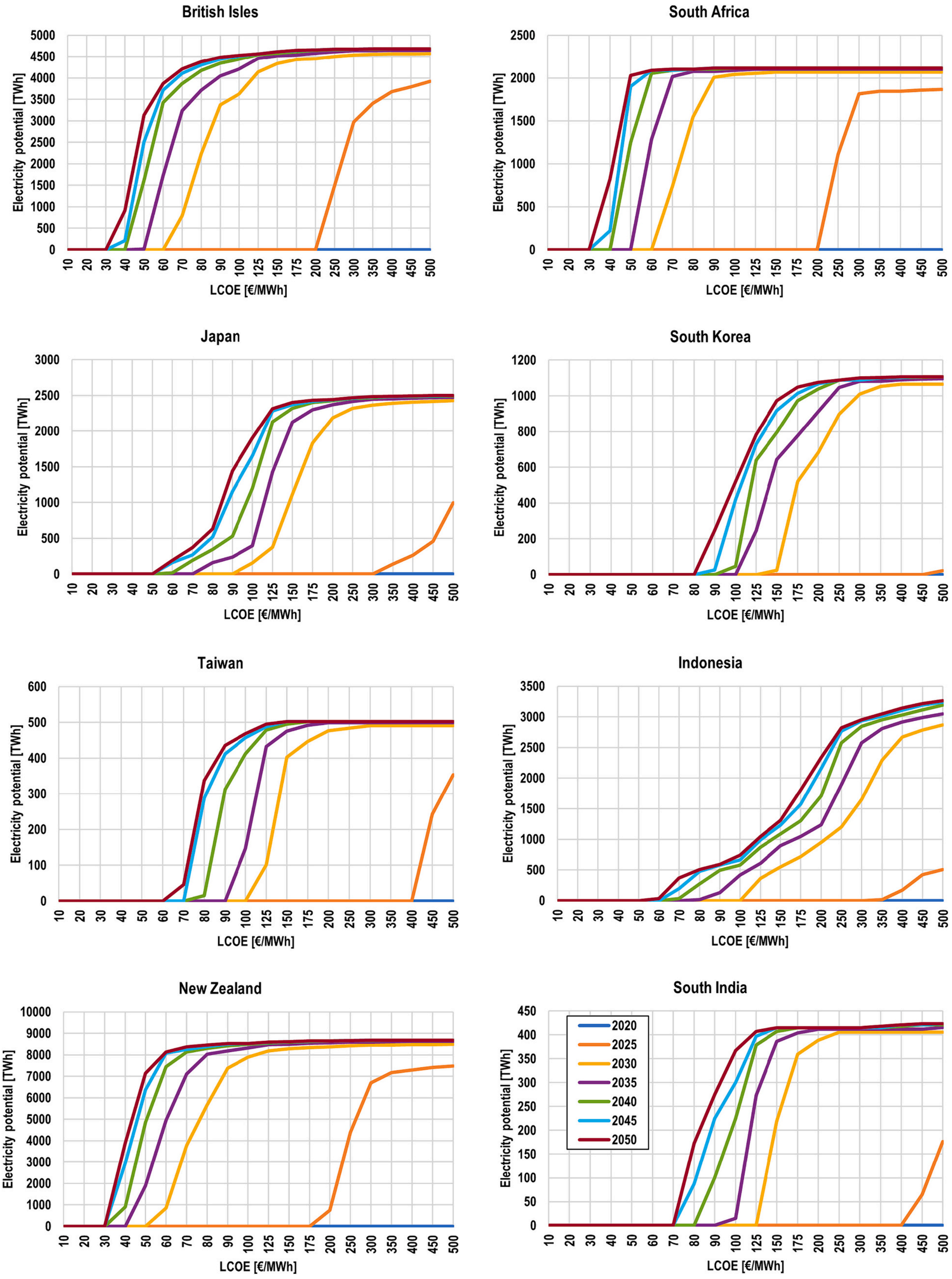

Fig. 13. Cost curves of the economic potential in specific countries around the world for point absorber WEC, showing the total electricity generation potential at a particular LCOE level.

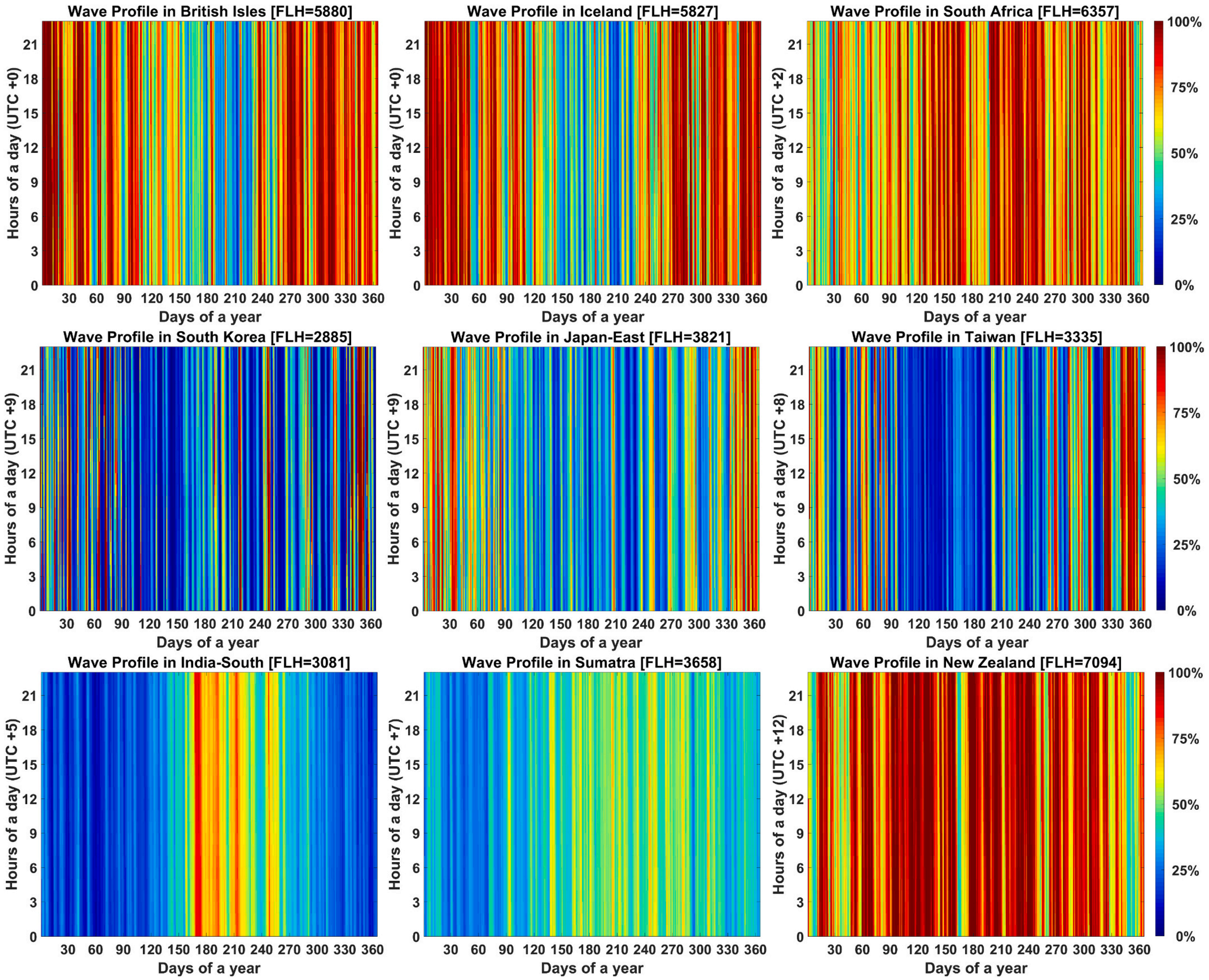
Wave Profile in British Isles [FLH=5880]
Wave Profile in Iceland [FLH=5827]
Wave Profile in South Africa [FLH=6357]
Wave Profile in South Korea [FLH=2885]
Wave Profile in Japan-East [FLH=3821]
Wave Profile in Taiwan [FLH=3335]
Wave Profile in India-South [FLH=3081]
Wave Profile in Sumatra [FLH=3658]
Wave Profile in New Zealand [FLH=7094]

Fig. 14. Hourly capacity factors of point absorber WEC in select regions, depicting hourly production in the vertical axis and daily to seasonal variance in the horizontal axis. The full load hours (FLH) are depicted in square brackets.

possible. Solar PV is found as the most relevant and least cost source of electricity for onshore energy systems [2,85] and has the chance to become a major technology for offshore energy systems development [9,101].

4.3. Limitations

The limitations of this study require consideration. First, the spatial resolution of input data is limited to 0.45°, which is equal to roughly 50 km by 50 km at the equator. Wave conditions and depth can change significantly within 50 km and the results of this study do not account for such differences. However, the dataset used in this study is a re-analysis dataset and its variables were merged and corrected via in-situ and satellite measurements.

These results cannot be used for the investigation of possible installation sites that would require more fine-grained data. Due to this limitation, this study assumed a 15% area utilisation for WEC installations, without considering the WEC farm length, orientation, or distance from shore. To put this limitation into perspective, a few possible WEC farm installation distances from shore are presented for the case of British Isles for the UK and Ireland in Fig. 16. The areas that are too far, too deep, protected, covered with ice, and outside the EEZ were filtered out (see section 2.3.3). Additionally, the areas with FLH below 2000 h were also filtered out to only keep the areas with high wave energy resources.

The black lines in Fig. 16 represent a point absorber WEC array of 2 km width installed parallel to the shorelines (line width is not to scale), as suggested by the EVOLVE consortium [102]. The case for 75 km distance was redrawn manually to attempt to determine the best alternative sites around the British Isles, in contrast to fixed distance lines in other cases. The hypothetical array length, power capacity of the array, electricity generation potential, and weighted LCOE based on financial assumption of 2040 are presented in Table 3. The calculations assume 1 km free space roughly every 10 km along the array for the passage of ships.

As can be observed from this approach, the British Isles for the UK and Ireland can tap into wave power with high FLHs at comparable LCOE values at different distances from the shore while remaining under the 15% area utilisation limit. To put the numbers into perspective, the total electricity generation potential for the 75 km case represents roughly 10% of the 4441 TWh total available electricity generation potential under 100 €/MWh, presented in Supplementary Material 2. Notably, higher FLH are attained at farther distance from shore with a 22% increase in FLH from 10 km to 100 km, but due to growing costs of

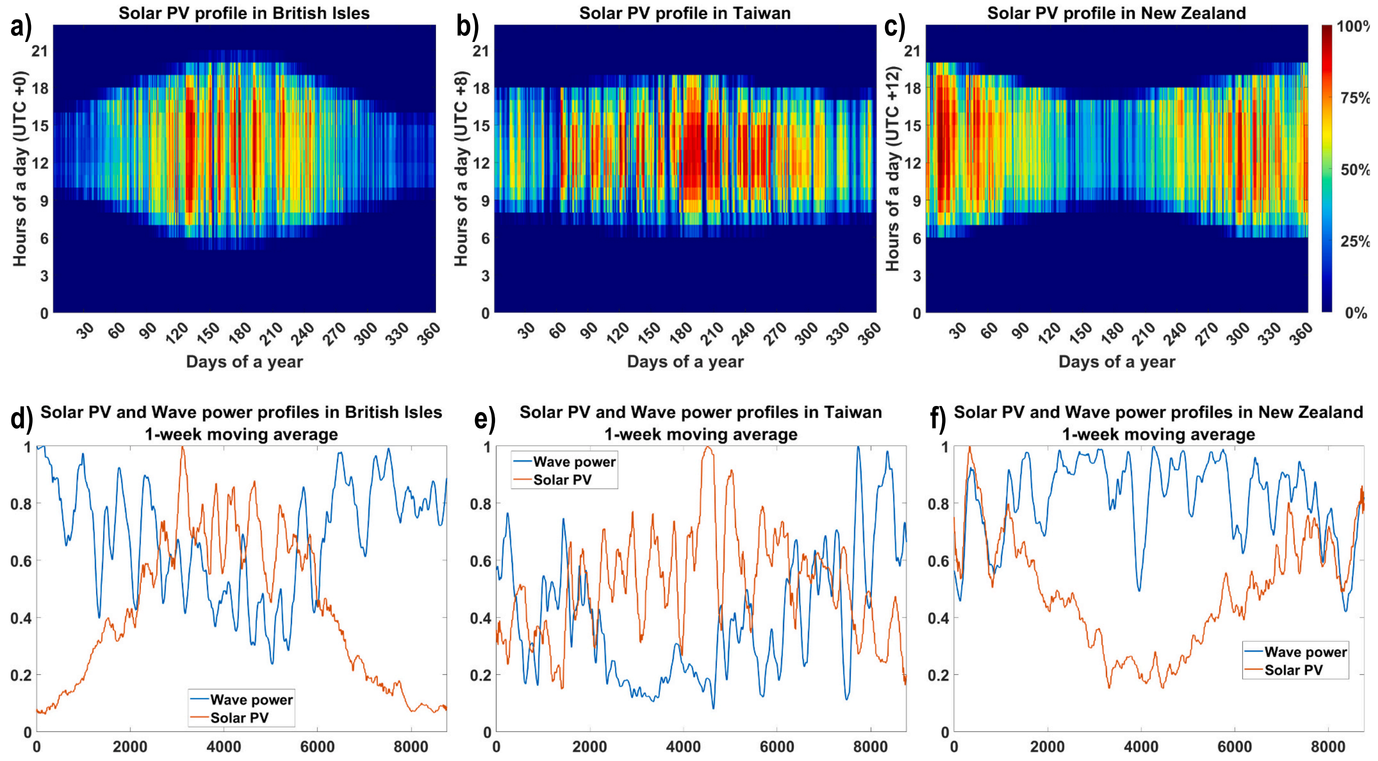

Fig. 15. Solar PV hourly capacity factors profiles (a, b, c) [91] and solar PV versus wave power one week moving average capacity factors profiles for British Islands (d), Taiwan (e) and New Zealand (f).

grid connection, the LCOE declines by “only” 14%. If wave power farms are deployed in such arrays along the shorelines globally, roughly 10% or 7035 TWh of the estimated global 70,356 TWh might be tapped around the world for the prime conditions of only one 2 km wide array parallel to the coastline for LCOE under 100 €/MWh and the year 2040.

However, it remains unclear if wave power can be harnessed in such a manner, where wave energy is absorbed by a ‘shield’ of wave farms. Further research is required to understand the rate of energy recovery in waves after passing through an array of WECs. The precise rate of energy recovery within waves depends on interactions between wind, local waves, and swells and the WEC used in the wave power farm. This issue will become increasingly more relevant when wave power installations grow worldwide. Moreover, the energy conversion capacity of each WEC within a wave farm is considered to be consistent in this study. The wake effects induced by the WECs in the front of the wave farm can reduce the significant wave height and peak wave period, leading to lower power production for the WECs at back end of the wave farm. Real world wave farms can have lower power production than the sum of the nominal power capacities of each WEC. Such nuances must be considered for wave power projects to optimise the dimensions of the wave farm for the best economic performance.

Second, the temporal resolution in this study is limited to 1 h and the wave characteristics can have sub-hour and sub-minute differences [103]. These results cannot be used to study the sub-hourly dynamics of wave power for power electronics. The resolutions were limited by the breadth of the research and the aim of the study is to assess the wave electricity yield available across the globe.

Third, one WEC was used for the techno-economic assessment. A broader techno-economic assessment requires technical and financial assumptions and projections of a more diversified sample of WECs. This study includes a nearshore point absorber WEC, while higher distances may be achievable in future. The considered WEC is optimised for depths between 30 m and 100 m, while in this study it was assumed that the technology can be further developed to access sites up to 1000 m of depth.

Fourth, this study did not consider the risks of extreme conditions severely damaging the WECs [104]. While the study factored in hourly weather conditions to prevent the WECs from generating power beyond the cut-off significant wave height and peak wave period, it did not account for extremely adverse sea states. Instances of exceptionally large waves or rogue waves can have the capacity to irreparably damage WECs. Future studies can improve upon this limitation by excluding areas prone to extreme sea states.

While the chosen technical assumptions and financial projection are considered reasonable based on current knowledge and industry consultation, the low maturity level of the technology and limited number of companies providing WECs and related expertise result in a higher level of uncertainty in these basic assumptions. That inevitably introduce uncertainties and limitations to techno-economical analyses, as outlined above, and affects the confidence levels associated with the results. Specifically, the cost analysis necessitates industrial mass production data to provide further support for the financial assumptions, more demonstrators and commercial farms are needed to remove uncertainties related to the wave farm efficiencies, availability factors and depth limits.

4.4. Future research

This study presents a global wave energy resource assessment to enable further investigations of the role of wave power in energy system analyses research. The resulting hourly capacity factors in a global-local scale enables the extraction of hourly wave power profiles for any region in the world. The inclusion of wave power in energy system studies can promote the development of the emerging wave power industry. The general benefits of wave power according to the literature [61,105,106] are higher predictability compared to other VRE resources, lower visual impact, and high power density, and continued discourse can facilitate bringing wave power to commercial utilisation.

Future research may build upon this study by using the results in energy system transition analyses. The resultant hourly wave power

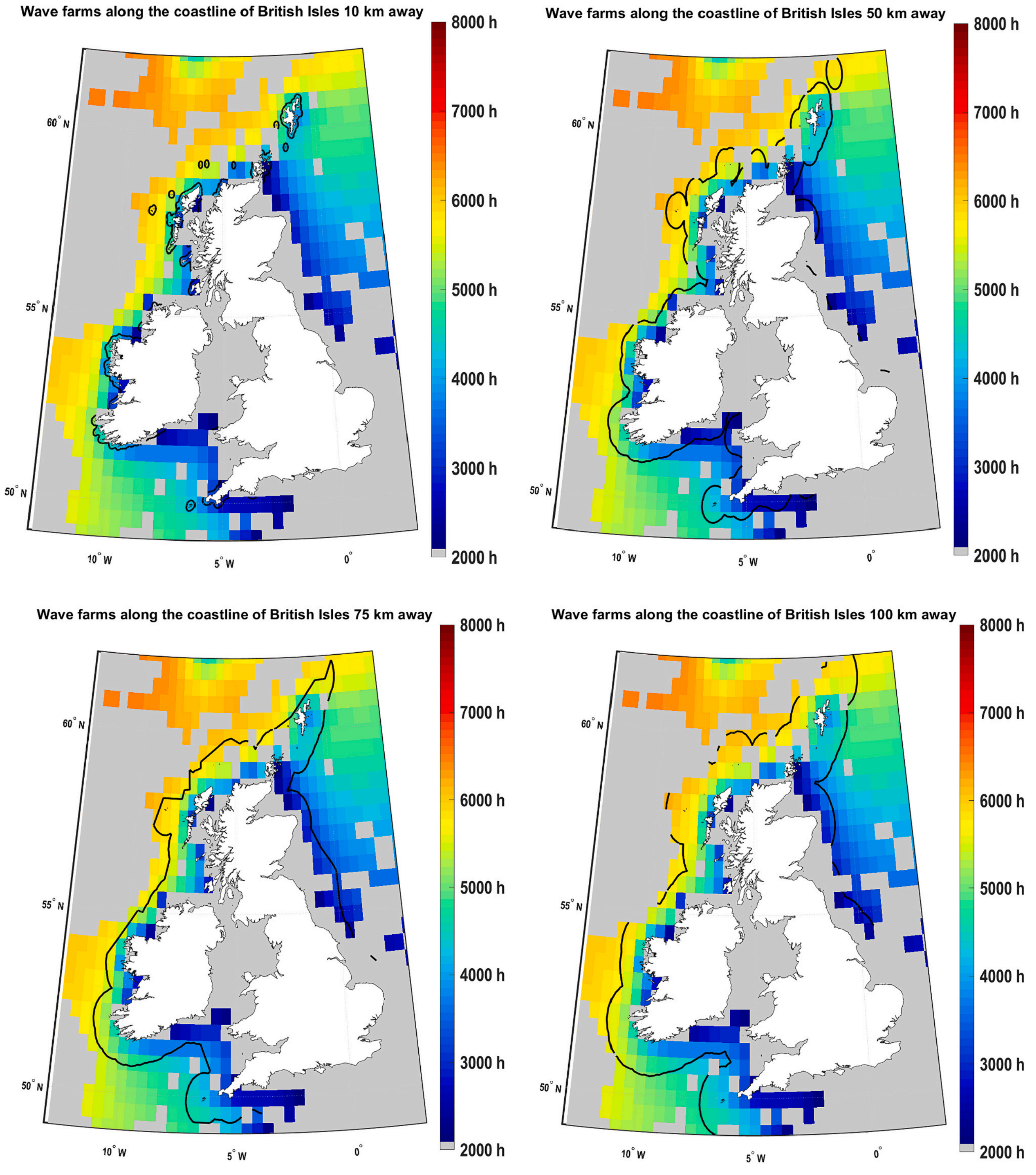

Fig. 16. Hypothetical wave farm installations along the coastline of British Isles for 10, 50, 75 (alt) and 100 km distances from the shore, depicted as thick black lines. The colourmap represents point absorber WEC full load hours within each cell, as shown on the colourbar. Additional details are provided in the main text.

profiles can be used in a simulation or an optimisation tool to investigate the role of wave power in an energy system, its interaction with other power generation technologies, and its impact on the overall energy system and cost structure. Future research can improve this study by including more WECs and more finely grained data, if reliable technical and financial assumptions are available.

5. Conclusion

This study estimates the technical and economic wave power potential in a global-local scale, considering the projections for technical and financial assumptions. While solar photovoltaics and onshore wind power can satisfy the energy demand in many regions in the world, wave power can become a strong contender to satisfy the energy demand for renewable electricity at all times, especially for land-constrained regions.

Table 3
Properties of a hypothetical wave farm along the coastline of the UK and Ireland.

Distance To Shore	Unit	10 km	50 km	75 km	75 km alt	100 km
Total Arrays Length	km	2964	4107	3379	3563	2689
Total Power Capacity	GW	80.8	112.3	92.5	97.5	73.6
Total Electricity Generation	TWh	329	506	441	469	365
Average FLH	hours	4071	4505	4770	4816	4959
Average LCOE	€/MWh	60.5	57.8	54.6	53.1	52

Many coastal areas with high population density and islands have a significant wave power potential that can contribute to the energy transition in these regions and increase local renewable energy supply. Mid-term projections indicate wave power competitiveness with onshore renewables and offshore wind power, suggesting a levelised cost of electricity below 100 €/MWh by 2030. In the 2030s, point absorber based wave power can provide 39,700 TWh of electricity for <100 €/MWh, 31,800 TWh of electricity for <60 €/MWh in 2040, and 29,000 TWh of electricity for <50 €/MWh in 2050.

Though solar photovoltaics and onshore wind power possess lower levelised cost of electricity, wave power can contribute to the diversification of energy supply, especially considering the complementarity of solar photovoltaics and wave power generation profiles. The wave power profile shows pattern of seasonality with more generation in winter than in summer, opposite to the solar pattern. Despite higher costs, wave power can reduce the need for medium term and seasonal storage, potentially lowering overall system cost.

Continued research and development, market growth-driven learning curves, and economies of scale will steadily reduce wave power costs, making it attractive to investors and policymakers, potentially matching offshore wind power levelised cost of electricity within a decade. Wave power can emerge to become an important source for coastal countries and regions with high population density and other factors limiting the onshore renewable energy potential, which otherwise would have to depend on energy imports.

CRediT authorship contribution statement

Rasul Satymov: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Dmitrii Bogdanov:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Mojtaba Dadashi:** Methodology, Investigation, Data curation. **George Lavidas:** Writing – review & editing, Validation. **Christian Breyer:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data used in the research is available in Mendeley Data [107].

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Appendix A. Supplementary data

The hourly capacity factors matrix with 400x800x8760 (row, column, hours) dimension is available at Mendeley Data [107]. The hourly capacity factors were calculated according to eq. 1, excluding the wave array interaction losses and availability factors. The resulting hourly capacity factors are freely available and can be used for research.

Additional figures depicting more details on results and input data are available in the Supplementary Material S1.

Detailed results on technical and economic potentials and further input data are available in the Supplementary Material S2. Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.123119.

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