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DOI

[10.1016/j.energy.2020.117131](https://doi.org/10.1016/j.energy.2020.117131)

Publication date

2020

Document Version

Final published version

Published in

Energy

Citation (APA)

Lavidas, G. (2020). Selection index for Wave Energy Deployments (SIWED): A near-deterministic index for wave energy converters. *Energy*, 196, Article 117131. <https://doi.org/10.1016/j.energy.2020.117131>

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Selection index for Wave Energy Deployments (SIWED): A near-deterministic index for wave energy converters

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ARTICLE INFO

Article history:

Received 4 December 2019

Received in revised form

29 January 2020

Accepted 10 February 2020

Available online 13 February 2020

Keywords:

Wave energy index

Wave energy converter

North sea

Variability

Capacity factor

Extreme values

ABSTRACT

This study introduces a novel index that accounts for the interactions of wave climate and wave energy converters, offering an unbiased approach that considers climate variability, survivability and energy production. Application of the index is done with use of a long-term wave hindcast, validated database for the North Sea. A detailed overall and monthly wave resource assessment reveals that mean expected wave resource is ≈ 15 kW/m, with higher nearshore values in December-January ≈ 20 –25 kW/m. Lower magnitudes are met in July with values closer to ≈ 4 –6 kW/m, as a general observation higher resource magnitude is expected at upper parts of the North Sea, with diminishing levels towards the English channel, the difference in available resource is almost half. The region favours "smaller" capacity devices for energy production, with capacity factors having encouraging results. The highest mean value for a capacity factor in the region is 25–32%, depending on device. However, the new index indicated that the highest capacity factor value should not be the determinant parameter. In fact, other locations have less energy production annually, but exhibit significantly less variation in production patterns, and lower extreme values of return waves.

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1. Introduction

Climate Change impacts are expected to have disastrous effects on human societies, with increased probabilities for extreme events, flooding, severe weather, and the socio-economic strata of human societies [1]. Amongst necessary steps to mitigate Climate Change, is the reduction of CO₂ emissions, several countries committed to ambitious targets at the Conference of Parties in 2015 [2]. European Union Member States have set ambitious targets for 2020 and 2030, with regards to greenhouse gas emissions and renewable energy [3]. Currently, National Energy and Climate Plans (NECPs) are under consultation, and it is clear that much has to be done in order to achieve the targets [4]. Common thread in all NECPs is the premise that all local renewable energy sources have to be used more. However, this premise encompasses several oversights and the need for innovative energies to be further incorporated.

Several studies have explored the feasibility of a 100% renewable energy future. Technically, all solutions exist that will take us to the new energy era. If all "hidden" externalities of fossil fuels and

nuclear are also included in public perception and policy making, it is obvious that minimum intrusive and least dangerous solutions for societal sustainability are renewable energies. However, as in all disruptive cases, viability criticisms of such systems have been raised see Heard et al. [5], but a detailed response was given in Brown et al. [6].

Jacobson et al. [7] showed that global energy systems dependent on Wind, Water and Sunlight (WWS) are feasible, with similar energy costs to current systems. The analysis utilised all available renewables (including waves), concluding that it will take ≈ 52 TW_{RES} [8], without compromising reliability and stability of the energy grid. Recently, Jacobson et al. [9] developed a roadmap for 139 countries comprised solely on renewable energies, this work estimated consequences avoided of ≈ 4.6 million deaths/annum and a significant reduction in energy poverty.

Zappa et al. [10] modelled several options for a European power system, with a target to reach 100% renewable energy. The findings indicated that ≈ 140 GW transmission grid reinforcements are necessary, and installed renewable capacities have to be ≥ 1.9 TW. Brown et al. [11] also modelled the European system showing the feasibility of high renewable systems, with $\geq 75\%$ in final energy use. The study also indicated interconnectivity between countries will have to increase, but such a scenario can achieve a 95% CO₂

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Nomenclature			
ΔT	Time duration (hours)	N	Return value investigated
$\hat{\sigma}$	Scale parameter for GPD	n_{years}	Years sample
κ	Length of dataset for GPD	$NECP$	National Energy and Climate Plans
λ_u	Rate of threshold for GPD	$p_{i,j}$	Probabilities of occurrence
λ_u	Threshold for GPD	P_{kDir}	Peak wave direction
$\overline{H_{m0}}$	Mean H_{m0}	P_o	Rated capacity (kW)
ρ	Water density (Kg/m ³)	P_{wave}	Mean wave energy (kW/m)
$\sigma_{H_{m0}}$	Standard deviation H_{m0}	PM	Power matrix (kW)
θ	Direction (Degree)	POT	Peak-Over-Threshold
ξ	Shape parameter for GPD	T_{m02}	Mean zero crossing wave period
$CapEx$	Capital Expenditure	T_{m10}	Wave energy period
CF	Capacity factor (%)	T_{peak}	Peak wave period
$CoV_{H_{m0}}$	Coefficient of Variation for H_{m0}	TW_{RES}	Terra Watt by renewables
E_o	Energy/electricity produced (kWh)	w	Watt
EVA	Extreme Value Analysis	WEC	Wave energy converter
f	Frequency (Hertz)	AWS	Archimedes wave swing
g	Gravitational acceleration (m/s ²)	BOF	Bottom Oscillating Flap
GPD	Generalised Pareto Distribution	$BShB$	Bottom submerged heave buoy
H_{EVA}	Wave return value with EVA in years	$F2HB$	Floating two body heavy buoy
H_{m0}	Significant wave height	$FHBA$	Floating heave buoy array
H_{max}	Maximum H_{m0}	$FOWC$	Floating oscillating water column
m	Meter	LNE	Lagnlee
		$SIWED$	Selection Index for Wave Energy Deployments
		SSG	Sea Slot-cone generator

emissions reduction when compared to 1990. High share of renewables in systems contribute positively to economic growth, reduce energy poverty and increase mobility [9,12,13]. In strict economic terms, the wholesale price of electric is reduced, regardless which variable renewable electricity source is utilised [14]. An optimal mixture is dependent on local resources utilisation, and high renewable energy penetration does not necessarily destabilise the grid. This of course means that high resolution modelling is expected to determine the impacts on prices by resource variations [15].

In most studies wind is expected to be a “base” load plant, with local resources availability differentiating the mixture. Some studies, included high fidelity assessment of multi generation [16,17], showing that as the energy fraction increases, a system can attain “stability” with wave energy, stabilising variable wind and limited solar production. Such an example is the case of Denmark, where it was estimated that as wind increases PV and wave are needed, with the wave resource obtaining a large significance due to its production profile [16]. The fact that wave energy is a complementary resource for wind, increases its value and potential for utilisation [17,18].

Wave energy presents a multi-layered challenge due to complexities in power production, and balances that must be achieved. Success in Wave energy converter (WEC) deployment is a combination of three main pillars: resource, extractable energy and economics (see Fig. 1).

The wave energy resource (P_{wave}) expresses the energy per unit of wave crest width in watts/meter (W/m). P_{wave} does not represent a value that is fully useable, energy produced depends on WEC characteristics. Energy refers to extracted energy by a WEC, using a power matrix [19], based on the statistical properties from significant wave height (H_{m0}), wave direction (P_{kDir}), and wave period(s) (energy (T_{m10}), peak (T_{peak})).

Economics refers, predominately, to the capital required for the development of a WEC. Majority of expenditure in a WEC is the Capital Expenditure (CapEx) which is a “one-off” cost. There is a

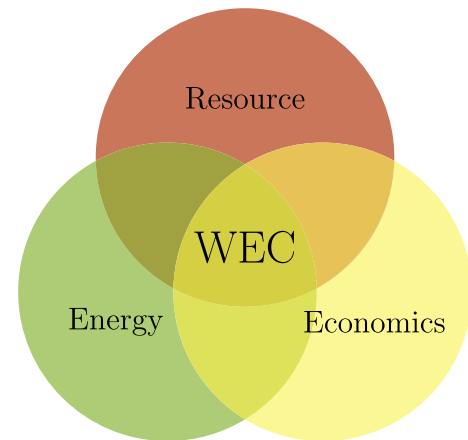


Fig. 1. Principles of balance for the development of any renewable energy technology.

diverse selection of WECs that are applicable at different depths, and have distinct construction requirements. For example a coastal WEC will require more CapEx for structures, while a floating WEC at deeper waters requires more moorings.

The methodology in this study proposes a new and condensed formulation to account for all different aspects, by reducing uncertainties and biases. The Selection Index for Wave Energy Deployments (SIWED), does not exclude expert judgement, but is rather an unbiased tool for the selection of an appropriate WEC.

Without expert knowledge in wave energy analysis, the index will do little to assist. However, the index can provide a robust approach to determine the optimal WEC for a location/region/area. SIWED provides an “optimal” selection, by considering long-term metocean variations that have negative effects on annual energy production. Finally, it considers climate implications of WEC survivability, and the negative effects high return wave values will

have on CapEx. The index, is applied to the North Sea region and the study also provides an assessment of dominant metocean conditions, levels of variation, and monthly analysis of wave parameters.

While, the author is fully aware that personal and/or technological biases will affect final selection, the index can offer a comprehensive comparison on a equal basis, in order to advance the untapped potential of this immense resource that can be accessed globally.

2. Materials & methods

Wave energy resource is amongst the most dense and predictable resources [20,21]. For a WEC one has to account for metocean conditions, extreme events, and of course achieve an energy production that will make the investment profitable. To understand the intricacies of WECs several studies have been published, providing good amount of information that underline the difficulty [19,22–25].

The issue of selecting a WEC until now has depend mostly on subjective expert judgement. Several authors have tried to develop methodologies and indices to assist in the selection of most suitable converter [26–31] and/or the suitable region [32–36]. Such approaches focus only on specific resource or device characteristics, a high energy content does not indicate that a location it will be an appropriate location. WEC production relies on resource availability and is often unique or within certain WEC(s) that share similar characteristics [37]. Limitations of past methodologies is that they either focus on resource, or only on energy production. They often do not investigate metocean trend interaction with energy production, and omit to consider extreme events.

2.1. Resource & climate variations

The basis for any application regarding renewable energies is quantification of the resource, this necessitates reliable information for proper identification of opportunities. Minimum required dataset for any renewable resource and proper energy quantification should be at least 10 years [38,39], a duration ≥ 30 years will ensure that Climate effects and trends are included in the estimations [40].

Waves are a summation of different wave numbers and frequencies interacting in the area, with propagated wave power depending on the energy density, with varied frequencies (f) and directions (θ), as expressed by the two-dimensional spectrum. The

P_{wave} for irregular (real) waves is given by Equation (1).

$$P_{wave} = \frac{\rho \cdot g^2 \cdot H_{m0}^2 \cdot T_{m10}}{64 \cdot \pi} \quad (1)$$

A higher resource should not be the the sole parameter, statistical properties of the resource should also be considered, with an important factor being the level of variation. Given the fact, that most important factor in wave energy estimation is H_{m0} (as it is squared), to assess the variability, the Coefficient of Variation (CoV) is used, see Equation (2).

$$CoV_{H_{m0}} = \frac{\sigma_{H_{m0}}}{H_{m0}} \quad (2)$$

The $CoV_{H_{m0}}$ can be considered a better approximation in assessing volatility, as it detaches itself from the mean value of the data. A low $CoV_{H_{m0}}$ value is closest to 0, indicating the location does not have much variation. The higher a $CoV_{H_{m0}}$ value is, more change in the resource should be expected, indicating volatility and perhaps that the region may not be as reliable for energy production.

However, $CoV_{H_{m0}}$ is not a limited range number, it can assume values from 0 to infinity, considering that H_{m0} only attains positive and theoretically infinite values. In the index, $CoV_{H_{m0}}$ is used to penalise the potential capacity factor as higher variability is a negative indicator. For this reason, $CoV_{H_{m0}}$ is reduced exponential i.e. as $CoV_{H_{m0}}$ increases resource effectiveness is reduced.

This relationship is important as it allows to distinguish not only high energy production associated with persistent conditions, but also introduce elements for the qualitative assessment of variability. As seen in Fig. 2, the higher a location's value then it is less effective, an ideal a location would have a high energy content for utilisation and low $CoV_{H_{m0}}$.

2.2. Energy production

There are many WEC concepts with different operating principles i.e. ways in which they absorb incoming wave energy [41], depending on the WEC there is also a possibility to have them dependent on wave directionality. However, developers do not offer information on the dependence of their device on directionality, and can differ significantly.

In Table 1, all WECs considered for analysis are presented, with potential applicable depths and the effects of directionality. It has to

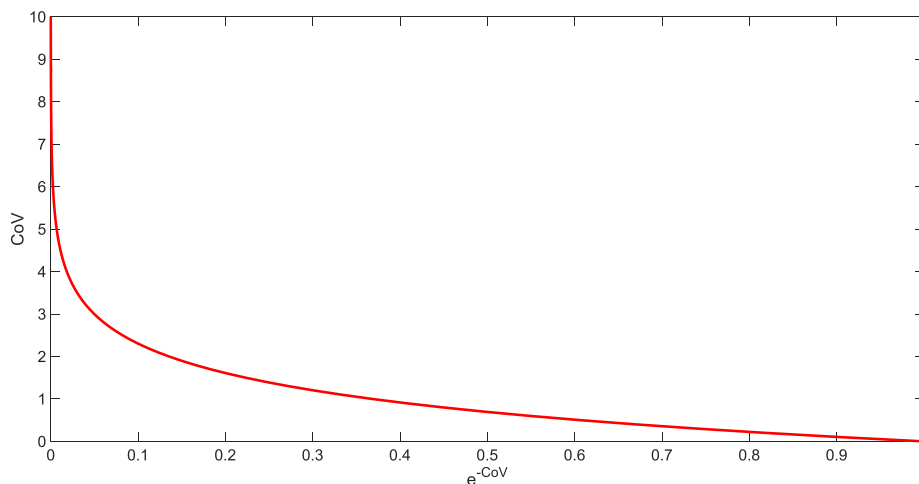


Fig. 2. The use of $CoV_{H_{m0}}$ and its exponential reduction, based on an “ideal” case. As the $CoV_{H_{m0}}$ increases the exponent decreases (e^{-CoV}).

Table 1

WECs used in this study as adapted by Refs. [19,30,31,43–50]. Depth: refers to the potential depth of WEC deployment and not distance to shore, $20 \geq$ Shallow, $20 \leq$ Nearshore ≤ 60 , $60 \leq$ Deep ≤ 150 . Abbreviations can be found in nomenclature.

Name	Type	Depth Application	Directional Influence
WaveStar	Point Absorber-Floater	Nearshore	Weak
BOF 1	Terminator	Nearshore	Strong
BOF 2	Terminator	Nearshore	Strong
Pelamis	Attenuator	Nearshore & Deep	Strong
F2HB	Point Absorber	Nearshore & Deep	Weak
WaveDragon	Overtopping	Nearshore & Deep	Weak
AquaBuoy	Point Absorber	Nearshore	Moderate
OceanTech	Attenuator	Nearshore	Strong
FOWC	Oscillating Water Column	Nearshore & Shallow	Moderate
BSHB	Point Absorber	Nearshore	Weak
FHBA	Point Absorber	Nearshore	Weak
SSG	Overtopping	Shallow	Weak
AWS	Oscillating Water Column	Nearshore	Weak
LNE	Terminator	Nearshore	Moderate

be noted, that when a WEC farm array is considered, pending on selected WEC, there can be positive benefits by wake effects [42], potentially improving energy production instead of reducing it. This is subjective and has to be analysed with further higher resolution time frequency domain models. However, if the resource analysis has highlighted dominant wave direction and directional spreading, then we can consider that the device is optimally placed as according to the influence of wave direction. In absence of substantial information all devices are assumed omni-directional.

WEC production is dependent on metocean characteristics of a location. The equivalent of a power curve, as in wind energy, for a WEC is the power matrix (PM) and represents the amount of energy that can be delivered, based on the probabilities of occurrence (p_{ij}) as estimated by the joint distribution of H_{m0} and T_{m10} or T_{peak} .

$$E_o = \frac{1}{100} \cdot \sum_{i=1}^{n_{T_{e/peak}}} \cdot \sum_{j=1}^{n_{H_{m0}}} \cdot p_{ij} \cdot PM_{ij} \quad (3)$$

Power produced is accounting all seastates, see Equation (3). Electricity production is dependent on nominal power, and as expected a larger name plate device will (theoretically) produce more energy.

$$CF = \frac{E_o}{P_o \cdot \Delta T} \quad (4)$$

nominal rated capacity P_o , the hours in a year (ΔT) and E_o energy produced (see Equation (4)). The Capacity Factor (CF) as a metric, “normalises” the performance, and presents it in a percentage and taking into account annual or time-dependent availability. This allows comparison of different devices, and a better look on the most appropriate. This term is used in numerical estimations on energy economics, providing the basis for normalization and even comparison of technologies. Indicative values in CF per technology are used by institutes, agencies for the aforementioned calculations of energy and economics [47,51–55].

2.3. Extreme events

Another important consideration when it comes to offshore structures, is their ability to survive extreme events. Estimation of wave return values are valuable for sizing of moorings, coastal structure, and strengthening work needed. Given the wide array of WECs that exist, return wave values can have a significant effect on CapEx.

Desirably the length of appropriate datasets, should not be less

than 20% of the desired return value [38,56]. The method used to estimate the extreme value analysis (EVA) is the Generalised Pareto Distribution (GPD) with a Peak-Over-Threshold (POT), as it offers more data points and can therefore increase the confidence [57].

The method for data preparation in this extreme value analysis is the POT, that can handle datasets of various temporal duration and lengths. Ensuring the recordings are not influenced by each other (identically independently distributed (i.i.d)) [58–60], threshold was set with the 99.5th percentile of H_{m0} with a 72 h windows. The choice took into account the available data and record its effects of the final data length [61,62].

$$z_p = u + \frac{\hat{\sigma}}{\xi} [(N \cdot \lambda_u)^\xi - 1] \quad (5)$$

$$\lambda_u = \frac{k}{n_{years}} \quad (6)$$

N (investigated) return value in years, λ_u rate of threshold, u threshold, κ length of dataset by POT, n_{years} sample duration, $\hat{\sigma}$ (scale) and ξ (shape) the GPD parameters.

The return wave period are calculated by utilizing the fitted GPD parameters of each location and based on the reduced sample rate as estimated in Equation (6) and Equation (5) with the Maximum Likelihood. Most WECs have an expected lifetime of 20–25 years, so a return value of 30 year ($H_{EVA} = H_{30}$) is deemed appropriate. This allows not to over-estimate extreme events and therefore increase CapEx.

2.4. Selection index for Wave Energy Deployments (SIWED)

The Selection Index for Wave Energy Deployments (SIWED) (see Eq (7)) proposed, aims to reduce the uncertainties and bridge the energy capabilities with resource dependence, providing an unbiased selection of WEC.

$$SIWED = \frac{e^{-CoV_{H_{m0}} \cdot CF}}{\frac{H_{EVA}}{H_{max}}} \quad (7)$$

$CoV_{H_{m0}}$ the Coefficient of Variation, CF the capacity factor, H_{EVA} the value of return waves based on extreme value analysis, and H_{max} the maxima value of wave height from the dataset.

If a region has high variability it is “penalised” by reducing expected power performance, since a higher volatility indicates a potential larger rate of change in metocean conditions. In the denominator, the ratio of the estimated return wave value over the

maximum significant wave height, assists in quantifying the extend of which return value differs in magnitude from the recorded maxima. This affects, WEC survivability, and if the ratio is too high it will probably require more CapEx to ensure long-term and safe operation. Theoretically, SIWED can obtain values close to unity, the exponential of $\text{CoV}_{H_{m0}}$ until, with a zero $\text{CoV}_{H_{m0}}$ i.e. no expected variation the term obtains a positive high value. In the event of a high $\text{CoV}_{H_{m0}}$, then the exponential drop near 0. The CF of a device can also acquire values up to 1 (100%), although for renewable energies this is not realistic. Finally, if no variation exists then the expected return value will be close to the maximum H_{m0} , theoretically obtaining a value up to 1. Therefore, if SIWED obtains a

higher value that means the site and selected WEC have a better “match” and can deliver reliable energy production.

3. Results

SIWED is applied to the North Sea Wave Database (NSWD) dataset covers a period of 38 years the database has an hourly output of parameters, with total $\geq 340,000$ hours per location [63], comparing different WECs for final selection. To evaluate and underline the usefulness of SIWED, several points were extracted along the domain, selection was arbitrary and made to represent a diverse set of conditions and depths, see Table 2 and Fig. 3. P_{wave} gives a multi-faceted overview of the intensity and magnitude of conditions, aggregated and seasonal analysis is vital to assess the performance. Guillou et al. [64] showed that seasonal variations are very important, as WEC performance can vary up to 50%.

North Sea conditions are mostly dominated by wind generated waves at the Southern part, and a mixture of wind and swell waves at the Northern [63]. Wave power (P_{wave}) can be clustered into three regimes (i) North of the Netherlands and West coasts of Germany have the “highest” resource, with magnitude at accessible depths from 10 to 18 kW/m, (ii) moderate/milder regions are at the central areas of the Netherlands, from $3 - 5^\circ \text{ E}$ and $53 - 54^\circ \text{ N}$ to $3.5 - 4^\circ \text{ E}$ and $51.5 - 52^\circ \text{ N}$ (Rotterdam) and $0 - 3^\circ \text{ E}$ and $52 - 53^\circ \text{ N}$ the coasts of Hull and Norwich, with magnitudes 6–10 kW/m, (iii) lowest resources are below Zeeland from 4 to 6 kW/m, and Ipwich from 2 to 4 kW/m, see Fig. 4.

The resource shows higher $\text{CoV}_{H_{m0}}$ at the English Channel,

Table 2
Extracted locations from the NSWD.

Name	Longitude	Latitude
Point 1	3.62	51.77
Point 2	3.31	51.75
Point 3	3.00	51.95
Point 4	3.28	52.00
Point 5	4.52	52.47
Point 6	4.27	52.49
Point 7	4.96	53.61
Point 8	4.66	53.28
Point 9	6.37	53.62
Point 10	4.02	54.12
Point 11	2.95	53.82
Point 12	4.73	54.85

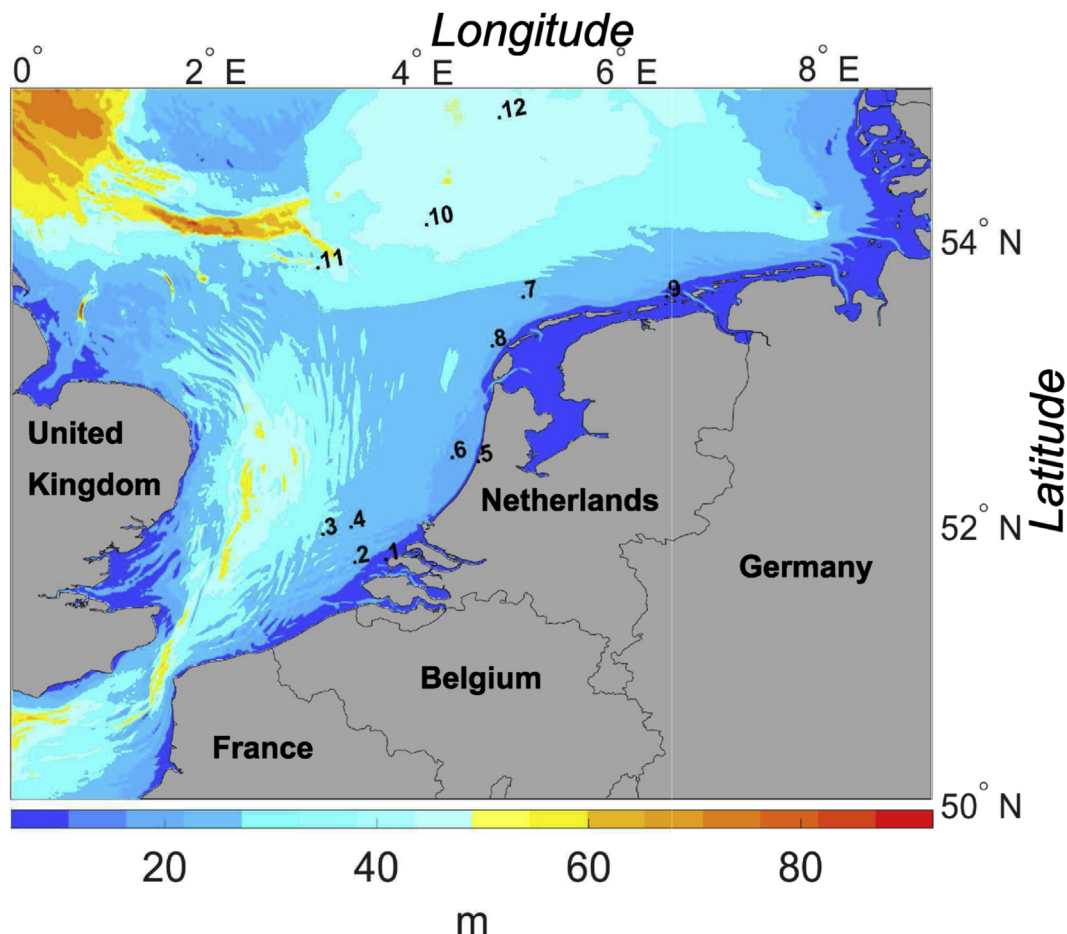


Fig. 3. Locations extracted and used by NSWD.

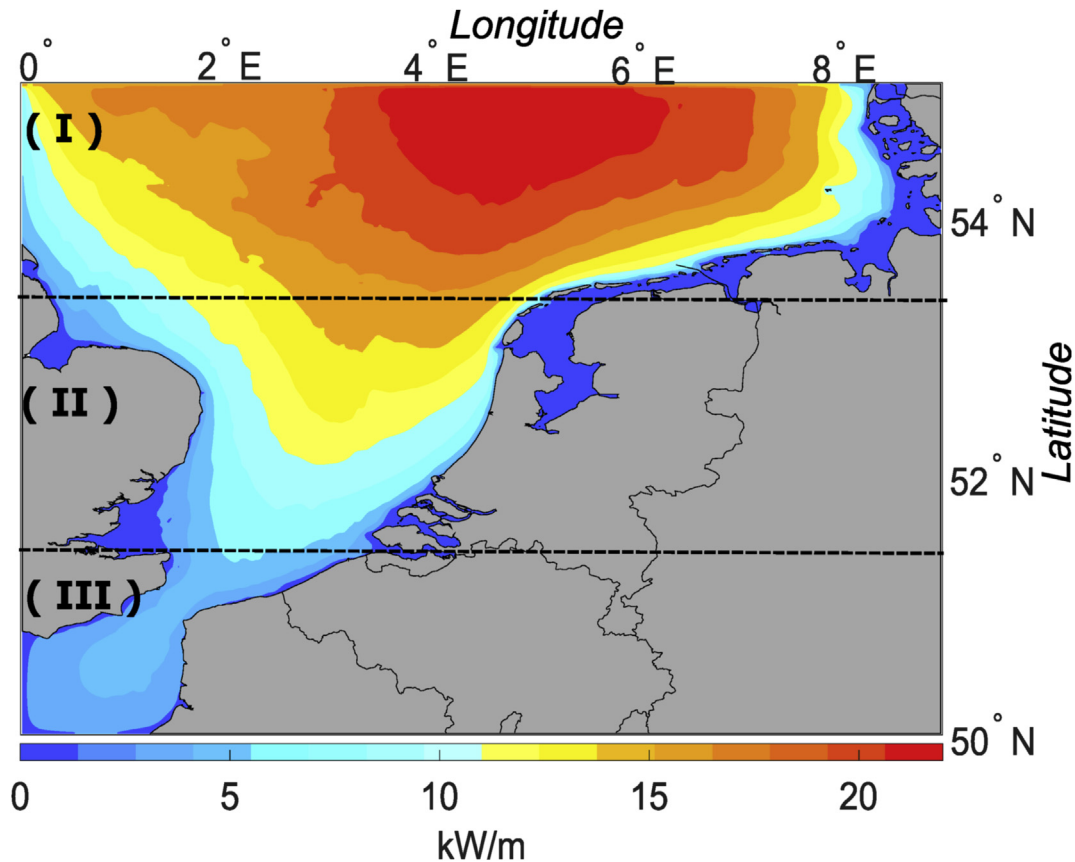


Fig. 4. Mean P_{wave} in kW/m for the whole dataset, separated in North Sea zones with (i) Highest resource zone, (ii) Moderate resource (iii) Low resource.

indicating that in the long-term conditions will experience changes. Lower $CoV_{H_{m0}}$ is found at Wadden islands (North of the Netherlands) with ≤ 0.15 . Southern areas close to the Port of Rotterdam $CoV_{H_{m0}}$ are moderate to low ≈ 0.3 – 0.4 , however, they seem to have neighbouring areas with higher expected rates, see Fig. 5. As a general observation, the North Sea has quite a high level of $CoV_{H_{m0}}$ magnitude, which can be detrimental for operations such as wave energy that depend on $H_{m0} - T_{m10/peak}$ without long-term variations occurring.

In terms of accessibility 70% of the time $H_{m0} \leq 1.5$ m that allows safe operations by vessels [37], see Fig. 6. High accessibility in combination with short shore distance and moderate depths, are beneficial for lower infrastructure costs, faster deployment and maintenance.

The highest wave energy magnitudes are met in the winter season of December–January–February (DJF) with January presenting the most energetic. Upper North Sea latitudes have higher P_{wave} , specifically the Wadden islands ≈ 25 kW/m. At deeper waters near that region propagated resource is consistently ≥ 30 kW/m, with values nearshore throughout DJF of ≈ 20 – 25 kW/m. The lowest conditions are encountered June–July–August (JJA), at the same area with magnitude ≤ 12 kW/m, a decrease of almost 50%. As expected autumn (September–October–November (SON)) and spring (March–April–May (MAM)) seasons are anti-diametrical, from MAM the energy flux slowly is reduced, and in SON it increases until it reaches in peak along the coastlines in DJF, see Fig. 7.

While wave power is an important parameter, another step is needed to further disseminate the potential. That is to analyse the spectral quantities which correspond to operating conditions of each WEC. Fig. 8 provides an overview of several different locations,

expressing the potential electrical (theoretical) production per occurrence, based on Table 2 and Fig. 3. The bivariate distributions provide a record of most dominant metocean conditions, the colorbar scale shows the theoretical energy that is available per sea state. This should not be confused with the extractable which depends on WEC characteristics. For each figure the joint probability distribution was also estimated (not-shown here), allowing the derivation of useful characterisation of dominant metocean conditions.

Most locations, show similar distribution of dominant metocean conditions within repetitive clusters. In terms of H_{m0} most locations, show highest occurrence probability within the range of 1.5 to 4 m, at Point 12 this is shifted to higher waves with most dominant characteristics from 2 to 6 m. Conversely, T_{m10} is also most prevalent within the ranges of 1–5.5 s, with Point 12 showing frequencies being most dominant for 3–9 s. These findings are also in line with the statistical analysis of percentiles for the H_{m0} and T_{m10} , which reveal that even for high percentiles (95th and 99th) the H_{m0} magnitude is below 6 m–9 sec and 5 m–7 sec, respectively, see Fig. 9.

WEC energy production is a fine balance between matching the resource, and having the “largest” installed capacity for a device/farm. Energy production is highly dependent on the conditions, so when it comes to energy production larger is not always better. Table 3 and Fig. 10, shows the assessment of all WECs, without any limitation on depth applicability, the figure offers an indicative overview of the potential energy production, through capacity factors (CF). As discussed in Ref. [50], directionality is expected to alter the generation profile, however, most information on directional effects are not shared in the open source power matrices, and

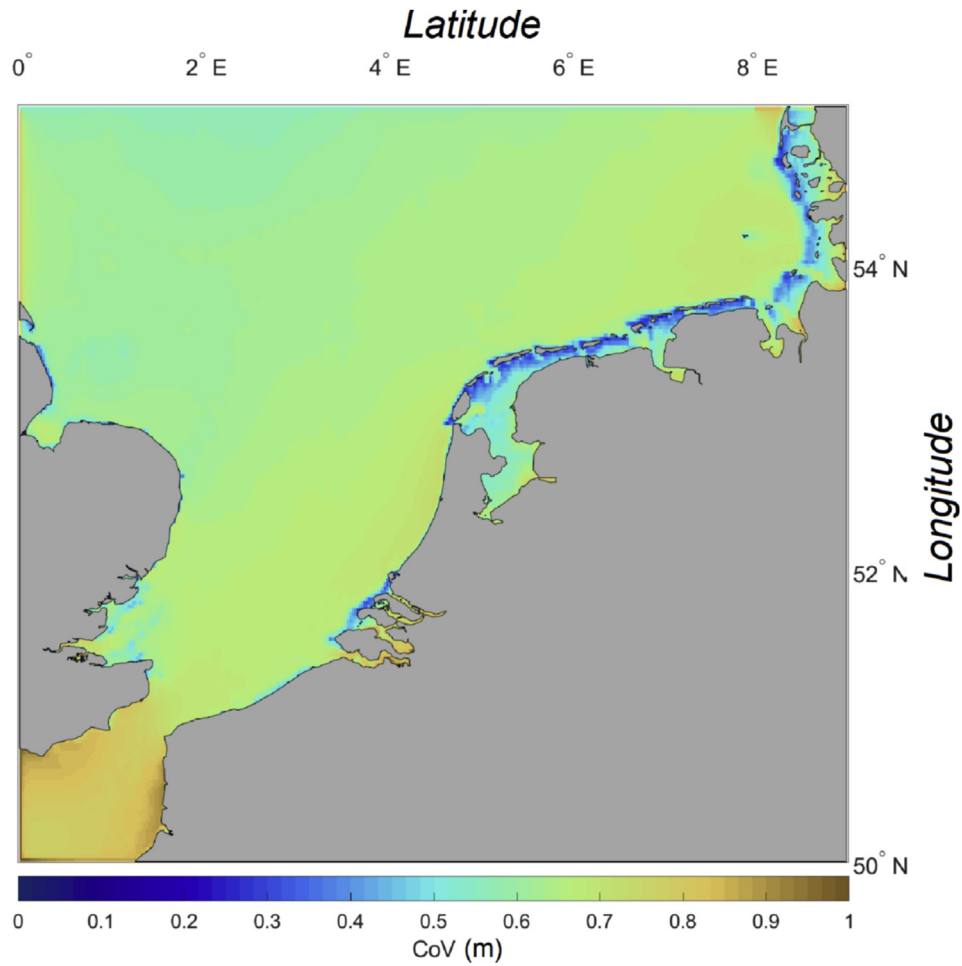


Fig. 5. CoV H_{m0} throughout the domain, based on the 38 year data.

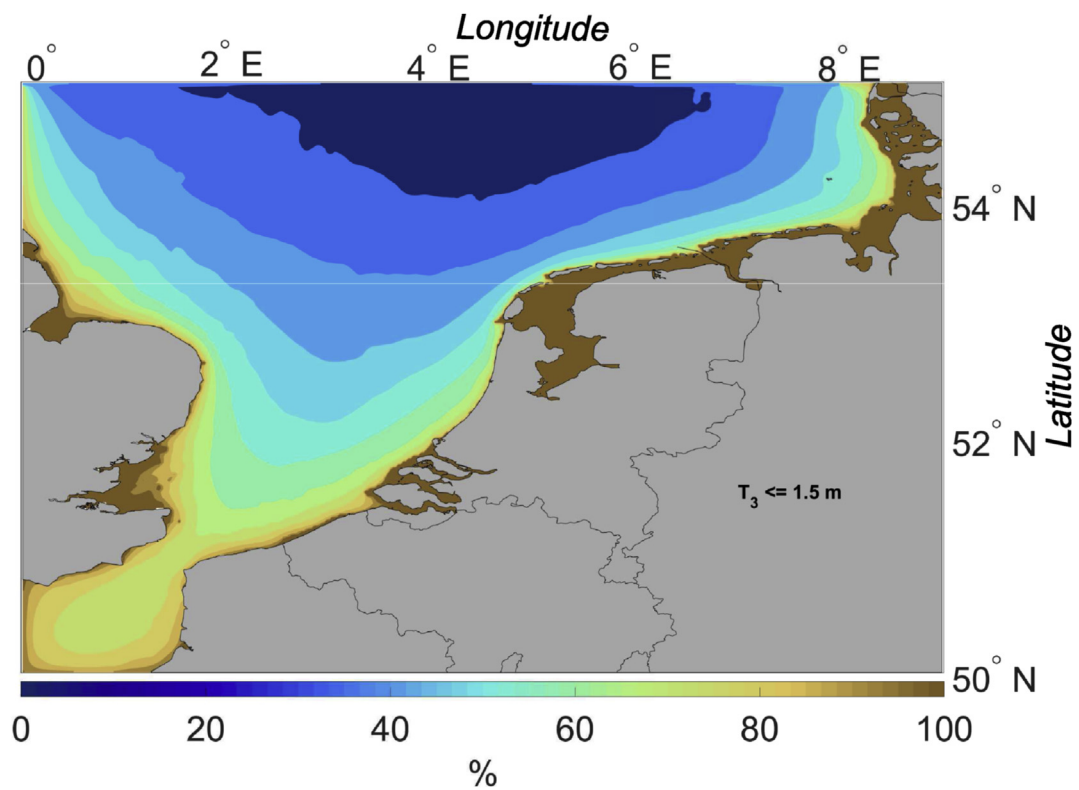


Fig. 6. Accessibility estimates for $0 \leq H_{m0} \leq 1.5$ meter, over the 38 years of NSW database.

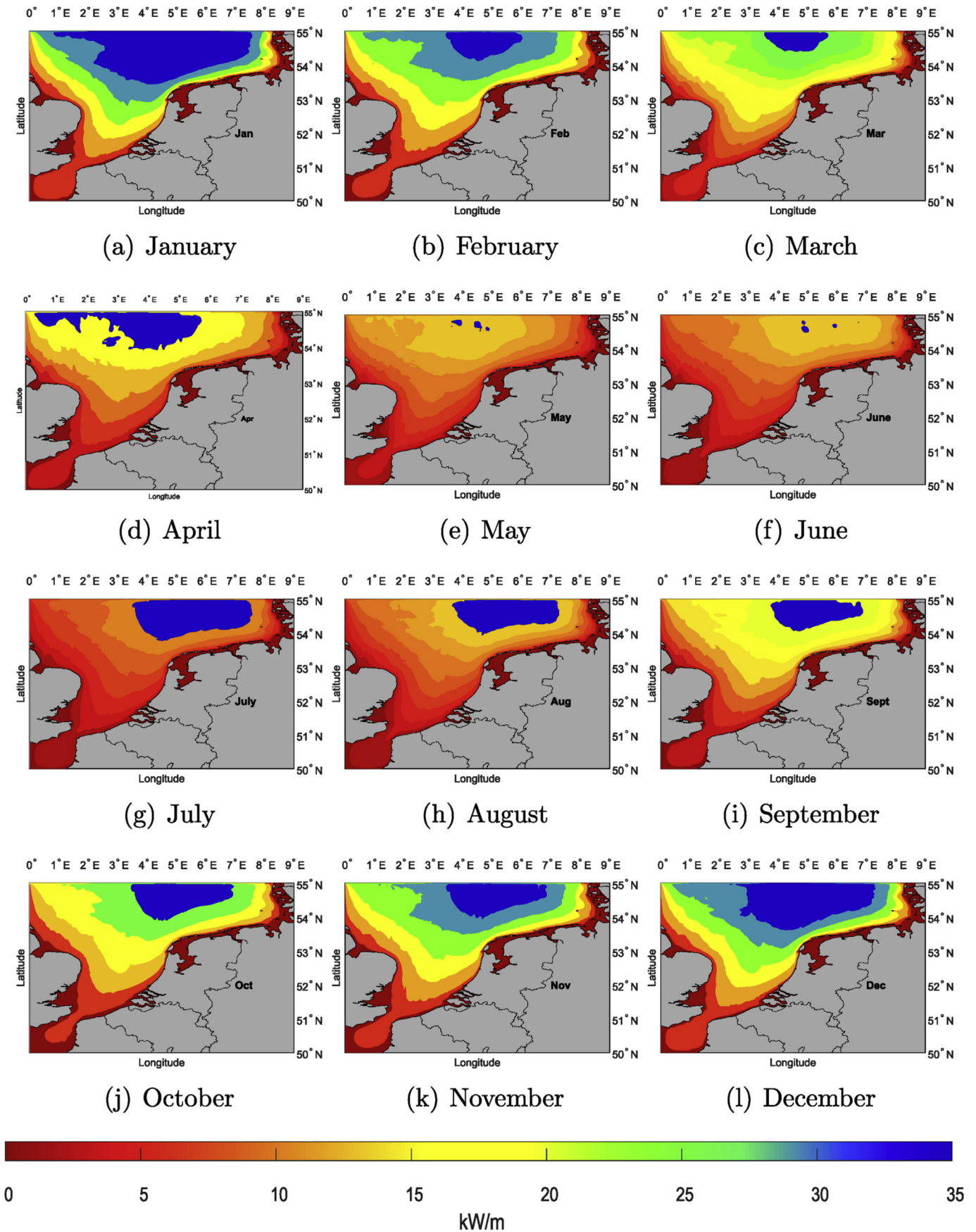


Fig. 7. Monthly mean P_{wave} in kW/m, the months all have been scaled to the highest potential.

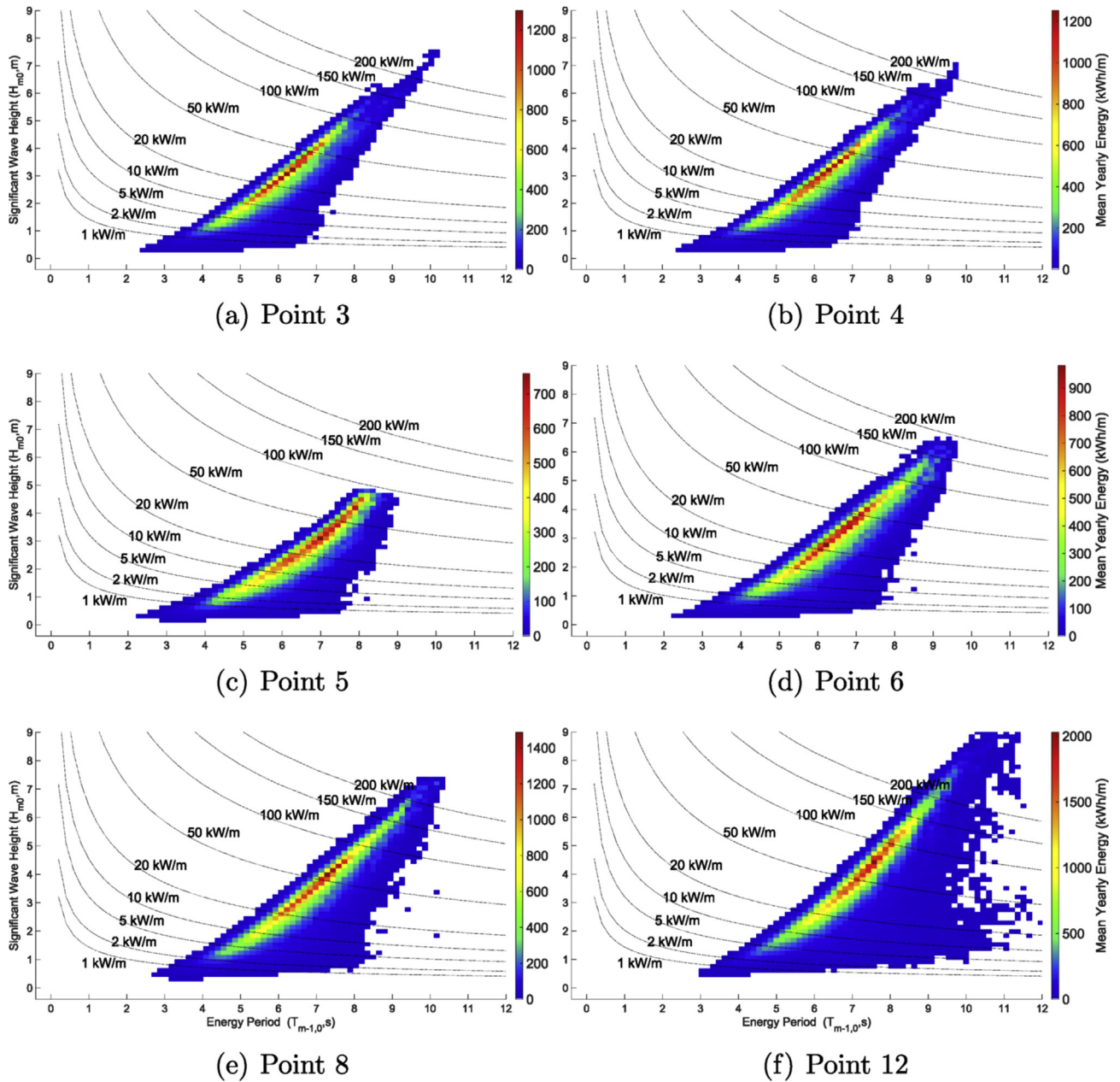


Fig. 8. Joint distribution(s) of several points extracted by the domain for all 38 years, coloured region express the theoretical energy that occurs from the joint distribution in kWh/m.

hence once a WEC is determined higher fidelity assessment may be necessary. Although, the effects of that are not expected to deviate much the CF potential, as when WECs are placed in a farm array, the wake and reflection effects may under specific scenarios also act as positive.

All locations and devices were assessed, it is clearly highlighted from Fig. 10 and Table 3, that in terms of potential energy production the OceanTech device performs extremely well, closely followed by WaveStar. All devices were applied to all locations to obtain an indicative “primary” assessment. SSG is a coastal device not applicable at large depths, however, its principle of operation can be adjusted to accommodate a floating design [44]. In this study the only viable locations for the SSG are point 1 and 5 which are located to the shoreline (see Fig. 3).

OceanTech outperforms most devices at nearly all locations, the

device is a small attenuator with characteristic length of 52 m, circumference of 7.5 m, and nameplate capacity of 500 kW. It reaches maximum potential at relatively low H_{m0} : 2.5 m and T_{m10} : 6 s, from Fig. 9 it is clear that these conditions are expected especially at Northern parts. Highest CF is recorded at Points 11–12 both of which are further ashore, however, the WEC shows promising results also at Point 7–9 with performance $\approx 30\%$. Towards the Southern coastlines, its CF reduces to 21%. Of course the WEC since it is an attenuator, is highly dependent on directionality [65], as stated prior no information on the direction exist, therefore for this WEC a small deviation of should be expected. Fig. 11 presents several grid points along the coastlines, the WEC has a consistent expected CF performance on average of 27–30%, after the English channel CF is reduced to $\approx 22\%$.

Less favourable WEC for this environment is the WaveDragon,

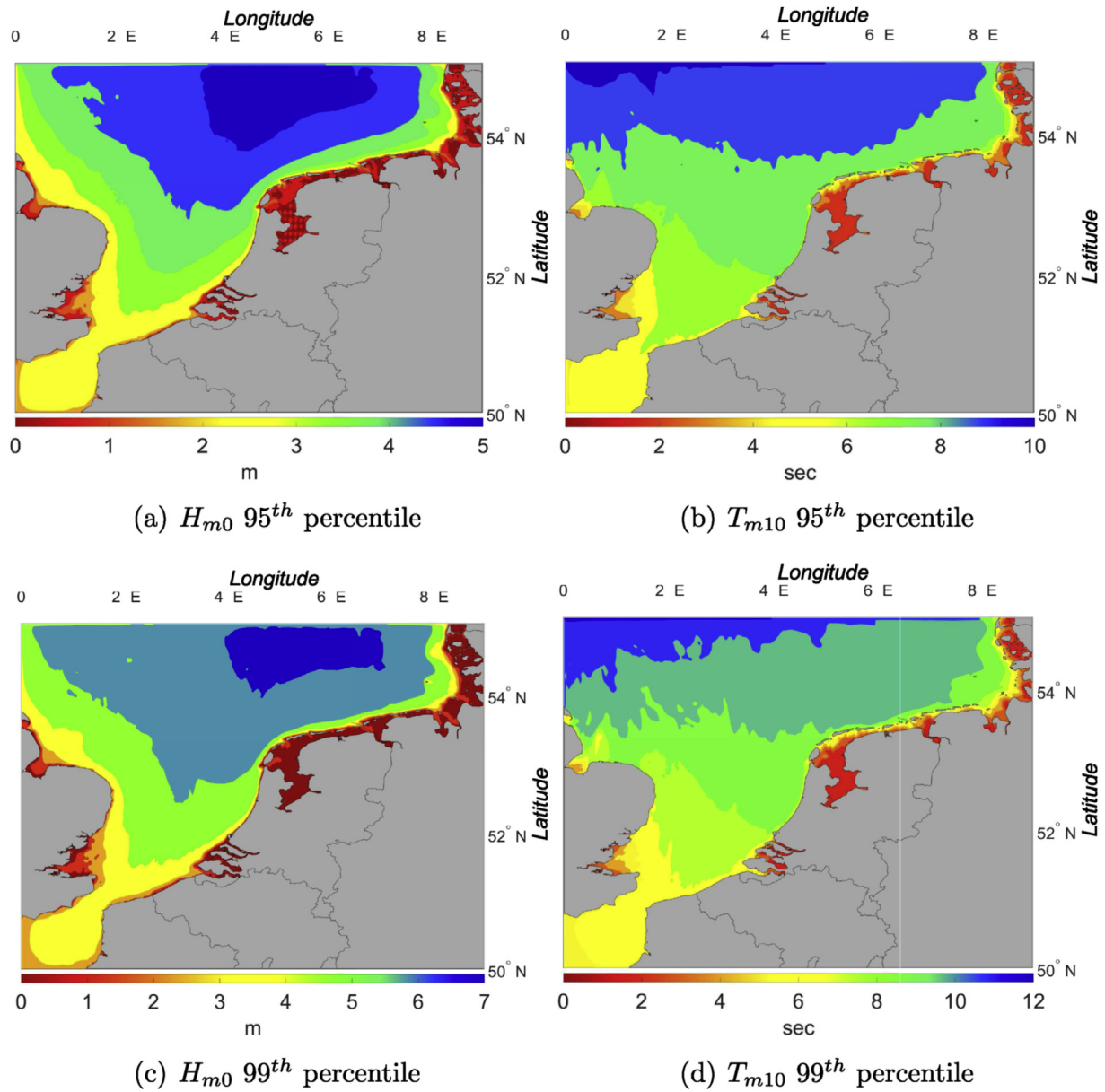


Fig. 9. Spatial distribution of percentiles (95th and 99th), for the values of H_{m0} and T_{m10} for the NSWD's database duration.

Table 3

Capacity factors for WECs at various locations extracted.

	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12
WaveStar	27,31%	23,21%	20,61%	21,89%	23,54%	23,25%	20,92%	22,68%	27,66%	21,21%	22,10%	23,72%
BOF2	6,81%	6,69%	5,59%	7,55%	7,86%	6,81%	7,17%	8,21%	11,68%	6,74%	7,68%	7,43%
BOF1	19,05%	19,38%	16,67%	19,63%	21,14%	19,59%	19,55%	22,29%	27,80%	18,66%	20,32%	20,03%
Pelamis	12,24%	14,28%	12,68%	16,19%	15,38%	14,60%	16,06%	17,89%	22,47%	14,71%	16,44%	16,11%
F2HB	6,90%	6,85%	5,69%	8,17%	7,96%	6,94%	7,53%	8,55%	12,17%	7,06%	8,34%	7,88%
WaveDragon	0,43%	0,83%	0,86%	1,30%	0,55%	0,68%	1,20%	1,16%	1,05%	1,17%	1,37%	1,28%
AquaBuoy	2,57%	4,94%	5,40%	9,74%	3,24%	3,96%	8,05%	6,89%	6,77%	8,24%	10,27%	9,37%
OceanTech	21,32%	25,39%	25,13%	30,29%	23,25%	23,32%	29,54%	29,65%	31,84%	29,66%	31,51%	31,89%
FOWC	2,68%	2,13%	1,69%	3,08%	2,84%	2,41%	2,77%	3,13%	4,75%	2,37%	3,09%	2,78%
BShB	9,92%	9,06%	7,83%	9,22%	11,60%	10,17%	9,69%	11,54%	15,94%	8,97%	9,08%	9,58%
FHBA	4,11%	4,56%	4,19%	5,19%	5,04%	4,68%	5,88%	6,06%	7,89%	4,33%	6,50%	5,02%
SSG	12,33%	n/a	n/a	n/a	12,06%	n/a	n/a	n/a	n/a	n/a	n/a	n/a
AWS	1,95%	2,60%	2,27%	4,02%	2,40%	2,62%	3,59%	3,69%	4,15%	3,02%	4,45%	3,44%
LNE	6,65%	6,21%	5,49%	6,54%	7,69%	6,64%	6,90%	7,91%	10,95%	6,22%	6,90%	6,73%

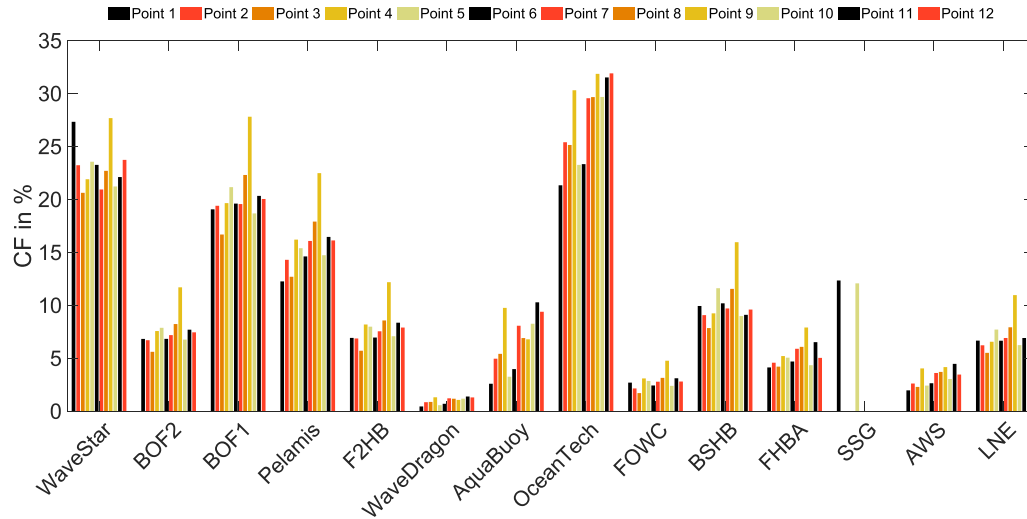


Fig. 10. Capacity factors for the extracted selected locations, the names and WECs used as seen at Table 1.

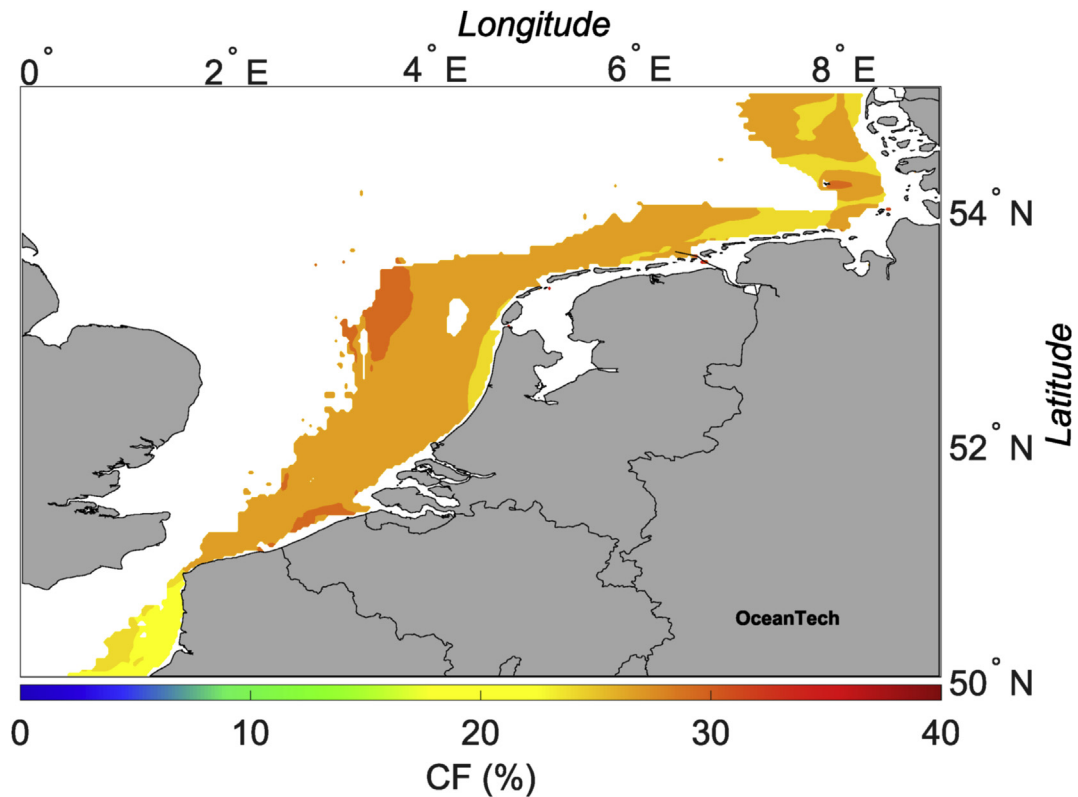


Fig. 11. Estimated CF for the “optimal” device (OceanTech) based on extracted location, examined for the domain of North with depth (d) limitation $10 \leq d \leq 30$.

an overtopping device with wave reflector and Kaplan turbines, more suitable for higher wave environments. Its nameplate is 7 MW (7000 kW) and obtained in sea states of at least 5 m H_{m0} and T_{m10} of 12 s. Such H_{m0} values are met in the North Sea but at higher latitudes, T_{m10} indicates longer swell conditions which are not often present. Its characteristic mass is ≈ 33 Tonnes with a width of 300 m and face length 170 m, that other versions of the device exist, however, their power matrices were not available.

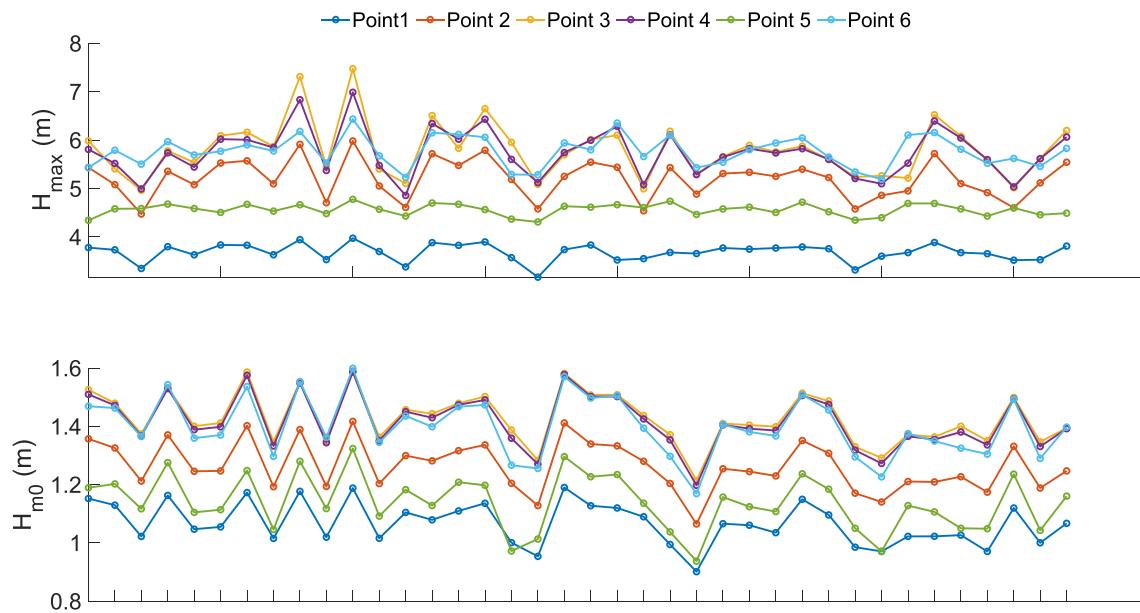
Closely following the optimal WEC is WaveStar, the device has a nameplate 600 kW at minima of T_{m02} : 4 s and H_{m0} : 3.5 m. The WEC is operative from T_{m02} : 3 s and H_{m0} : 1.5 m. When compared

OceanTech the device operates $\approx 6\%$ better at Point 1, but performs less for rest of the locations. The device trailing third, is the first iteration of a BOF, and achieves its highest at Point 9, but has good enough performance for remainder locations $\approx 20\%$.

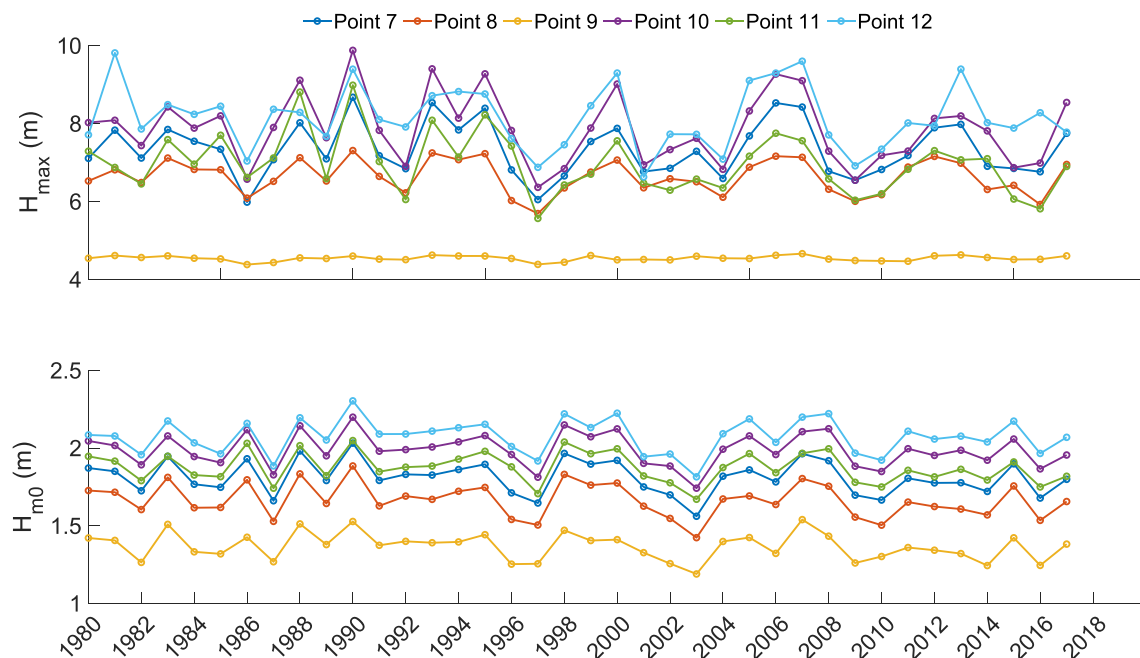
CF is not the only consideration when it comes to WECs, farms are expected to be deployed for at least 20 years, therefore probabilities for “harsh” conditions must be assessed through a complete extreme value analysis to ensure survival. Different return wave period were estimated for all locations, see Table 4 and when compared with the info by Fig. 12, it is evident that there is a difference to the maxima values, that are usually considered for

Table 4
Overview of metocean conditions characteristics, P_{wave} and return values for H_{m0} in (m) for different targeted years considering the expected life-time of a WEC farm, using a GDP-POT methodology.

	$H_{EVA_{10}}$	$H_{EVA_{20}}$	$H_{EVA_{30}}$	P_{wave} (kW/m)
Point 1	6.95	8.82	10.28	4.62
Point 2	9.08	10.83	12.06	6.94
Point 3	7.34	7.91	8.26	8.92
Point 4	8.41	9.46	10.15	8.92
Point 5	10.10	13.94	17.17	6.33
Point 6	12.29	15.82	18.51	9.25
Point 7	10.88	12.36	13.35	16.07
Point 8	14.93	19.70	21.41	13.48
Point 9	6.08	7.07	7.85	8.67
Point 10	9.88	10.68	11.16	19.60
Point 11	9.14	9.96	10.47	16.52
Point 12	12.92	15.00	16.40	21.4



(a) Locations extracted Group A



(b) Locations extracted Group B

Fig. 12. H_{max} and $\overline{H_{m0}}$ values for locations.

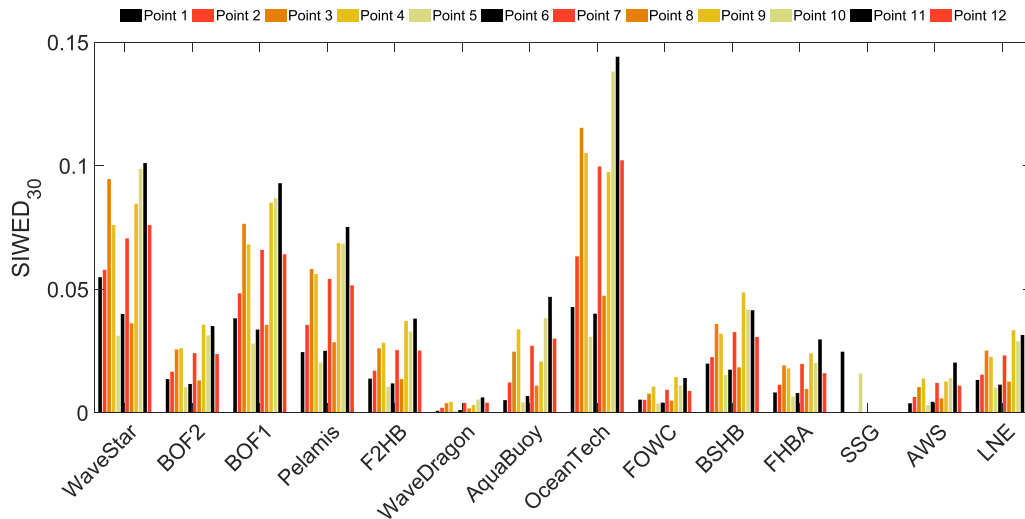


Fig. 13. Assessment of $SIWED_{30}$ indices for all WECs.

survivability and sizing purposes.

As in the case of any resource dependent quantity, values tend to have some annual fluctuations. Both for mean ($\overline{H_{m0}}$) and maxima (H_{Max}) locations values have been plotted to underline the significant differences that occur, see Fig. 12.

For first set of locations (Group A), $\overline{H_{m0}}$ shows similar trends throughout the years, starting from 1980 there seems to be an increase in means every 2–3 years. The shallowest location is Point 1, as depth is affecting the propagated wave annual $\overline{H_{m0}}$ has ± 20 cm fluctuations from 1 to 1.2 m H_{Max} does not show great differences. Similar depth range is also at Point 5, with $\overline{H_{m0}}$ having similar behaviour magnitudes, and $H_{Max} \approx 0.5$ m more than Point 1. Remainder locations are further away from the shore, close to the English channel, where the resource is lower, hence the reduced $\overline{H_{m0}}$, however even at these locations the annual variation is ± 20 –25 cm. In contrast, H_{Max} exhibits greater variance with some instances being ≈ 2 m more, see 1989 and 1990. For Group A there seems to be a greater fluctuation at maxima until 2001 a stabilisation until 2011, and a sudden increase in 2012, see Fig. 12.

Group B are areas at higher latitudes at the North Sea, common characteristics of these locations is that they are exposed to incoming Northern swell waves, that propagate from the Norwegian Sea, and swells from the Northern Scottish islands. $\overline{H_{m0}}$ is ≈ 1 m higher than the mean values of Group A, however the exposure to higher swell waves is translated in larger magnitude H_{Max} waves, supporting the largest annual and monthly higher P_{wave} resource. Northern regions are exposed to higher maxima fluctuations, and may increase potential storm flooding and over-topping. The variation in maxima values is also higher with “repetitive” reductions every ≈ 3 –4 years followed by and increase. It has to be noted that $\overline{H_{m0}}$ does not follow the same trend, although it does indicate an increasing trend. The highest variation from year to year maxima is exhibited by Point 10 and 12, both location near centre of the domain highly influenced by swell waves.

The highest energy performance is exhibited by OceanTech for all locations, however not all Points should be considered favourable. Highest production is at Point 12, but simultaneously the $CoV_{H_{m0}}$ is larger with a high return value. On the contrary Points 3, 7, 10, 11 can be considered much better, since they have lower extremes, $CoV_{H_{m0}}$ and a CF 25–30%.

A prominent example of the index usefulness to detach from mere energy production, is the WaveStar case, that can also be

considered suitable, with obvious advantage the omnidirectionality. Locations with the highest CFs are Point 1 and 9, however most suitable locations to deploy the device are 3, 4, 10, 11. In order to assess which device has to be selected, all information of climate, energy potential production, extreme analysis have to be considered, SIWED offers an unbiased selection, see Fig. 13.

4. Discussion and conclusions

From the comparison, it is evident that the principle of operation should not be the main criterion for selection, in this study three different WECs based on different principles can be considered viable. Findings seem to be in agreement with the suggestion by Falnes that “small is beautiful” [66], as most favourable devices have smaller name plate capacities ≤ 1 MW. The devices have smaller characteristics in terms of power production, but are more suitable for resource that are classified as moderate. In terms of energy production the analysis shows that several devices have CFs $\geq 20\%$. The performance of the WECs is in accordance with other studies that evaluated similar WECs at moderate resources [26,31]. This can potentially be beneficial for device adaptation to a larger number of regions [67].

However, fine balances between resource, WEC “match” and extremes should also be part as main selection criteria, as they affect energy production and costs. SIWED is a first step in the feasibility evaluation for WEC farms, providing unbiased information, as much as possible. With the suggested approach all potential WEC technologies can be assessed by also taking into account the metocean condition variability, and extreme events, resulting to a more custom “resource-to-production” approach. Engulfing all elements necessary not only for highest energy production, but also consistency and enhanced survivability considerations. As shown, in the SIWED analysis, while a device can have a high energy production, extreme conditions at a location, which affect survivability, can be higher than a location with slightly lower production but better survivability. The interactions between metocean conditions and potential energy performance, are the vital components for selecting suitable region. The analysis should always considered suitable long-term conditions that will allow a better representation of opportunities for energy production, and quantify the threats by variations and extreme conditions.

SIWED can assist in selection and cross comparison of either location(s) or WECs or a mixture of both. It encompasses and

assigns quantifiable values to qualitative characteristics, and clearly shows that moving away from the “strict” notion that wave energy is only suitable for highly energetic environments is obsolete. In terms of energy performance, a suitable selected WEC, even at a first generation stage, has CF and energy production similar to other mature renewables. Regardless of exposed resource, SIWED can provide holistic evidence based arguments on the energy performance and interactions with the resource.

In this study a novel index (SIWED) is introduced for optimal exploitation of wave energy. Unlike, previous attempts this formulation encompasses components assessing a WEC holistically. SIWED aims to provide an unbiased way to “optimally” select a suitable device and location.

Dominant North Sea metocean conditions indicate operative ranges for WEC(s) of H_{m0} : 1.5–4 m and T_{m10} : 3–9 s. The 95th percentile suggests majority of H_{m0} is below 5 m and 7 s, revealing a high availability for conditions $H_{m0} \leq 1.5$ m. North Sea nearshore areas have $\geq 90\%$ availability, moving further ashore at $10 \leq d \leq 30$ m this reduces to 70–85%. Higher levels are encountered at the English Channel, with values consistently $\geq 85\%$. $\overline{H_{m0}}$ at Northern regions is from 1.5 to 2 m, while at Central and Southern regions values decrease to 1.2–1.6 m. However, long swells originating from the Northern boundary, and the often occurring storm increase the annual maxima magnitudes from 6.5 to 10 m, and 4–7 m, respectively.

P_{wave} is moderate to high, with nearshore areas from 10 to 20 kW/m, with Northern Holland encountering the most energetic resource. Seasonally and monthly distribution favours winter months with highest levels ≈ 20 –30 kW/m at accessible regions with small distance from shore. Far-shore locations have consistently ≥ 35 kW/m, similar $\overline{H_{m0}}$ spatial distribution, even in winter months P_{wave} at the English Channel is ≤ 10 kW/m, and central parts of the North Sea have 10–20 kW/m. The reduction of available wave power in the domain, between high and low seasons is 50%, with summer months having smaller $\overline{H_{m0}}$ values and wave power ≈ 10 kW/m.

SIWED evaluated several locations and 14 WECs, and even at the milder resource of the North Sea most WECs achieved good energy production. Six WECs with different principles of operation, showcased a capacity factor of $\geq 10\%$, with three having $\geq 20\%$. For all locations highest CF was obtained by an attenuator CF: 31.89%, followed by a point absorber CF: 27.6%, and a bottom oscillating flap with highest CF: 27.8%. All three devices have a relatively small installed capacity, but are all able to produce their maxima production at ranges of H_{m0} : 2–4 m. The “smaller” capacity, indicates smaller size i.e. less material which can lead to potentially lowering CapEx.

For decision making SIWED reveals more characteristics, even though at its “suitable” location the WEC has a CF: 31.89%, conditions are severe and would compromise survivability. On the contrary, optimal locations for the same WEC are Points 3,10,11, with the latter two having a high CF: ≤ 1 –2% from Point 12. Point 3 was almost 8% less but its extreme wave return values was 43–50% less, and has a “concentrated” occurrence profile.

Acknowledgements

The author would like to thank the reviewers for their constructive comments, which helped at improving the manuscript. The author would also like to thank Bahareh Kamranzad, for her inputs in the early stages on developing the index.

The Research Fellow and WAVE Resource for Electrical Production (WAVREP) project has received funding from the European Union's Horizon 2020 research and innovation programme under

the Marie Skłodowska-Curie grant agreement No 787344.

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