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Shifting wave energy perceptions: The case for wave energy converter (WEC) feasibility at milder resources

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ABSTRACT

Wave energy can provide significant benefits as renewables acquire more share in electricity production. So far, focus for the development of wave energy is given to areas with resources $\geq$ 25 kW/m, with moderate resources often not considered. Furthermore, waves have larger uncertainties associated with diverse portfolio of converters leading to higher Levelized Cost of Electricity (LCoE).

This study challenges the notion of economic viability for moderate resources, therefore the methodology and results of this analysis are globally applicable. Several different types of wave converters suggest multi-zonal applicability, underlying the dependence on the diverse wave energy resource that can be harvested. It is clear that different zones favour alternative converters, common characteristic is that all have nominal capacity below 1 MW. Optimally selected converters, attain capacity factors over 30%, with LCoE depending more on discount rate-capital pairs, mean LCoE values are from 150 to 250/MWh with lowest value 60 €/MWh. Investment amortisation also depends on resource and LCoE pairs with an offshore wave farm able to retrieve its capital in 3.8 years (optimal case), 10 years (average). Projects with $\geq$3 Million €/MW and a higher risk discount of 10% are viable only for high performing devices with capacity factors $\geq$40%.

1. Introduction

The 2015 Paris Agreement set ambitious plans to curb the catastrophic effects of Climate Change [1]. The European Commission developed a Green New Deal initiative, from which several parts became European legislation in 2020 and onwards [2,3]. Major focus of this Green New Deal is to promote renewable energies, with novel technologies front and centre, for Europe to maintain clear leadership, ensuring trade and services are carbon free or near neutral. The European Commission is committed to achieve the Paris Accord, translating this into tangible 2030 targets: reduction $\geq$ 55% greenhouse gas emissions,$\geq$ 32.5% for share of renewables in the electricity system, and $\geq$ 21.5% energy efficiency.

Spearheading the first wave of the transition are mature renewable energies, such as hydro, wind and solar. However, these will not be enough to maintain flexibility and power stability [4,5]. Scenarios suggest that higher renewable penetration can be achieved partially by increasing interconnectivity, but it will still require short term power flexibility ($\leq$ 48 hours) from storage. For example in the Netherlands, certain scenarios proposed a 15–17 GW of storage capacity, without accounting for climate change and alterations in climatic conditions [4].

Similar issues are facing several countries in Europe and globally, as they transit to electricity systems with high share of renewables. To actively reduce energy dependency from imports and increase resilience, multi-generation has to be taken into account. Scenarios have been simulated at global [6] and on local level [7,8], with hourly and sub-hourly estimations of renewable energy production. Arguably, multi-renewable generation offers significant advantages in reducing the variability, especially at systems that highly depend on wind and solar [9–12], and in the long-term energy costs are decreased [13,14]. Multi-generation of renewable energies can also address other issues such as water scarcity, through desalination [15].

Wave energy is one of the most dense, predictable and persistent energy sources, that has gone under-utilised [16], with many countries exposed to it. Depending on orientation with regards of coastal fronts to swells and global energy flux distribution, resources can be characterised as high, moderate and low [17]. Fairley

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Nomenclature

ΔT	Hours in a year
C_n	Total expenses
c_o	Electricity price
e	Energy reflation
H_{m0}	Significant wave height
n	Year(s)
P_{wave}	Wave power
r	Discount rate
R_n	Revenues
T	Lifetime
T_{m02}	Mean zero crossing wave period
T_{m10}	Energy wave period
T_{peak}	Peak wave period
AEP	Annual Energy Production
AWS	Archimedes Wave Swing
BOF	Bottom Oscillating Flap
BSHB	Bottom Submerged Heave Buoy
CapEx	Capital Expenditure
CF	Capacity Factor
D	Diameter
ETS	Emission Trading System
F2HB	Floating two body Heavy Buoy
FHBA	Floating Heave Buoy Array
FIP	Feed-in premium
FOWC	Floating Oscillating Water Column
GW	Giga Watt
km	Kilometers
kW/m	Killowatt per meter
L	Length
LCoE	Levelised Cost of Energy
LNE	Lagnlee
M	Million
MW	Mega Watt
NER	New Entrants Reserve
NPV	Net Present Value
NSWD	North Sea Wave Database
S	Salvage value
TRL	Technology Readiness Level
WEC	Wave Energy Converter

et al. [18] globally assessed the resource, and underlined the similarity of wave period values between moderate and low classes having higher presence. Wave resource persistence is region dependent, but Climate Change effects have increased the resource by 0.4% kW/m/year since 1948 [19], predominately at deeper ocean regions where converters are not deployable.

Globally, the long term rate of change in global wave power shows that high latitude regions (60^o N–90^o N) have experienced a reduction in wave energy content, and lower latitudes (30^o S–60^o S) have positive a increase [20]. In terms of metocean condition at European coastlines high latitudes have increased [21], while the Mediterranean Basin shows a higher stability with smaller variations [22]. Kamranzad et al. [23,24] used a Climate Stability Index to assess the Southern Indian Ocean from 1979 to 2003 and a forecast from 2075 to 2099. The findings showed an increase in Southern Indian Ocean regions, up to 15 kW/m in some areas. However, variability levels indicated lower monthly differentiations when compared to the Northern Indian Ocean, that indicate a more consistent resource.

The large presence of moderate wave power resources, has prompted the suggestion of mild energy and low variability areas as most suitable [18,25,26], suggesting that new devices should be optimised for such areas. This can be done not only by differentiating the size of a converter, but also by adjusting control strategies to obtain higher amounts of extracted power at different conditions [27–29]. Such optimisations in control strategies can differ per converter type, but they can increase power production from 20 to 45% [30]. Lavidas [31] introduced a methodology to select wave converts that account for energy production, resource variability and survivability using high fidelity hindcast data from 1980 to 2017, establishing the method. Its application to moderate areas, revealed that lower variability areas can indeed provide higher energy production and attain better survivability, without increasing capital expenditure.

Although, everything points to the high potential contribution of wave energy systems, there are still significant obstacles in accelerating their deployment, predominately associated with energy costs [32–34]. Initial studies estimated the cost (in Million €) per installed MW (M€/MW) from 3 to 10 M€/MW [35,36], this larger range represents the uncertainty that comes by wave energy converters of various TRL. However, as wave energy interest is increasing and novel installations are financed [37,38], more specific cost data are analysed.

Encouragingly monetary requirements have reduced, within a range of 2–6 M€/MW, dependent on device and infrastructure works needed [39,40]. The Levelised Cost of Energy (LCoE) reported has a range of values from ≈ 120–500 €/MWh [25,41–43], underlying the uncertainties which are dependent on device, resource and assumptions. De Andres et al. [40] discussed the ranges for capital and LCoE with a target price at 0.15 £/kWh. Several devices were considered and costs from ≈ 2 M€/MW to ≈ 6 M€/MW. The LCoE reduction potential of several subcomponents, was achieved through a "reverse" approach that had as a starting point the desired LCoE and identified potential cost reductions to achieve it.

This study explores whether mild resource can be cost-effectively exploited, by properly attributing a "production-to-resource" approach, that so far is not considered. The question answered is whether mild resource are viable for wave energy. This premise is often dismissed without much consideration or evidenced arguments. In terms of wave power production potential, the wave density potential (kW/m) is not the determining factor. Results indicate clearly, that the potential is significant and alter the perception of non-viability for wave energy converters.

The difference of our analysis is that it seeks to "optimise" economic performance by placing an optimal device, based on long-term energy terms. The analysis compares available technologies on an equal footing with a 38 year metocean dataset, only with a predefined limitation according to depth applicability. The methodology presented showcases that conditions matter much more than the nominal installed capacity or starting cost. As WEC farms are installed, they will benefit immensely by learning rates reductions [35]. In this study we assess a variety of costs and concluded, if done correctly, that wave converters are comparable with other mature renewables in energy production, and have high potential to leverage capital expenditure reductions.

The energy capabilities at the North Sea remarkably have capacity factor ranges higher than previously thought, as the lack of comprehensive dataset was a major limitation. The methodological approach used is based on best-practises, minimising assumptions, and extrapolations on economic feasibility only on single points.

The results provide a holistic approach of what is feasible, what are the most favourable WEC dimensions and regions they should be deployed.

The results of our study provide a comprehensive multi-layered techno-economic assessment that for the first time assessing wave energy converters at the North Sea. It was found that techno-economic viability depends on specific criteria, and it is shown that for milder resource smaller wave energy converters are more suitable. The outcomes and discussion can be easily transferred to other similar resource regions as they tend to have analogous operative conditions (i.e. Mediterranean, Black Sea), therefore repeatability is high, with only sensitivity energy policy and market push/pull mechanisms.

2. Materials & methods

Estimation of wave energy is dependent upon the quantification of metocean statistical characteristics, and utilisation of a power matrix [44]. For all locations within the NSWD occurrence probabilities and propagated energy was estimated. Every seastate has been clustered and occurrence probabilities have been calculated, extracted locations indicate higher probabilities for significant wave heights H_{m0} 1.5–3.5 m and T_{m10} 1–6 s, see (a) Fig. 1. The figure shows mean energy contained per clustered event, it is important to note that this is the theoretical.

To assess the economic and financial feasibility of devices, within the study expected energy performance was used as indicated by the power matrices. To estimate energy performance, climate metocean data provide the probabilities of occurrence ($P(H_{m0} \cap T_{peak/m10/02})$). The North Sea Wave Database (NSWD) which is thoroughly calibrated and validated for the North Sea from 1980 to 2017 [45,46]. The duration of the NSWD extents from 1980 to 2017 (end of 2017) and developed with a modified nearshore spectral wave model, with a spatial resolution of ≈ 2 Km in latitude and longitude. The accuracy of the database is high, with validation of results compared with in-situ H_{m0} measurements having accordance of ≥ 93–94% and positive biases of a few centimetres. The model performance index for all years and location was above ≥ 95% indicating good performance. Lavidas [31] noted that the North Sea wave energy flux at the area can be classified as moderate, with persistent values at the nearshore between 7 and 12 kW/m, see Fig. 2.

All devices used in the study are presented in Table 1 and can be found in Ref. [31], the power production capabilities are estimated by Equation (1), and the capacity factor from Equation (2). It has to be noted that some WECs based on their type and principle of operation depend on wave direction, i.e. they have to be perpendicular to the wave front. This in turn may have effect in the joint distribution of metocean conditions that will affect Equation (1). However, directional matrix information are not usually publicly shared, and therefore solely based on the type of WEC one may infer the potential influence of directionality.

LCoE is a metric often used in energy comparisons with Technology Readiness Levels (TRL) [34,47,48]. LCoE can carry inherit flaws based on assumptions around economic indices [34,49] and most importantly Annual Energy Production (AEP) (see Equation (3)), often based on single or limited (≤ 10) years which are highly flawed. This is the reason why many researchers, groups and organisation proposed ≥ 10 years for reliable LCoE assessment [34,50–52].

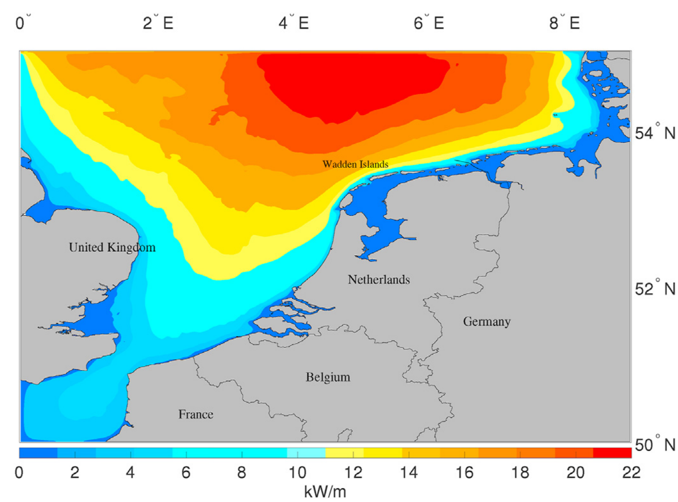


Fig. 2. Mean P_{wave} in kW/m based on analysis from the NSWD database from 1980 to 2017 (38 years).

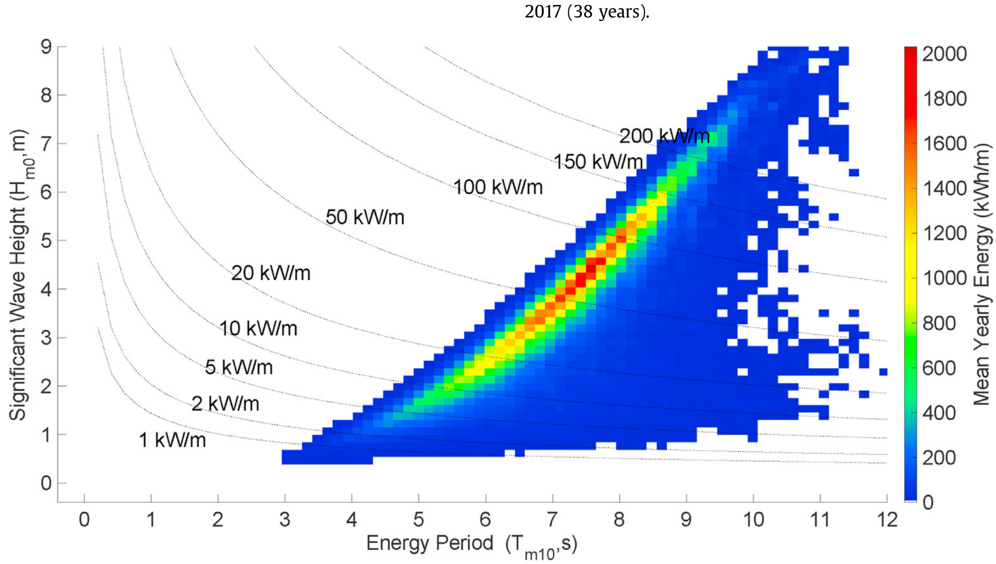


Fig. 1. The joint bivariate matrix for a location within the NSWD, with coordinates 4.72° longitude and 54.85° latitude. The colormap indicates energy contained within each bin.

Table 1
WECs used in this study, Depth (D): refers to depth of WEC deployment and not distance to shore, to 20 ≥ D (Shallow), 20 ≤ D ≤ 60 (Nearshore), 60 ≤ D ≤ 150 (Deep).

Name	Type	Depth Application	Directional Influence
WaveStar (600 kW)	Point Absorber	Nearshore	Weak
F2HB (1000 kW)	Point Absorber	Nearshore & Deep	Weak
AquaBuoy (250 kW)	Point Absorber	Nearshore	Moderate
AWS (2470 kW)	Point Absorber	Nearshore	Weak
BSHB (260 kW)	Point Absorber	Nearshore	Weak
FHBA (3619 kW)	Point Absorber	Nearshore	Weak
BOF 1 (290 kW)	Surge	Shallow	Strong
BOF 2 (3332 kW)	Surge	Shallow	Strong
Langlee (1665 kW)	Surge	Nearshore	Moderate
OceanTech (500 kW)	Attenuator	Nearshore	Strong
FOWC (2880 kW)	Oscillating Water Column	Nearshore & Shallow	Moderate
WaveDragon (7000 kW)	Overtopping	Nearshore & Deep	Weak

$$AEP = \sum_{i=1}^{T} \cdot \sum_{j=1}^{H_{m0}} \cdot (P_{H_{m0}} \cap T)_{i,j} \cdot PM_{i,j} \tag{1}$$

$$CF = \frac{AEP}{P_o \cdot \Delta T} \tag{2}$$

with the probabilities of metocean conditions ($P_{H_{m0}} \cap T$) for significant wave heights and corresponding wave period, that can either be peak wave period (T_{peak}), energy period (T_{m10}) or mean-zero crossing (T_{m02}). PM is the power matrix of each corresponding device as characterised in cartesian coordinates (i,j), and ΔT being the time duration for the gathered probabilities.

$$LCoE = \frac{PV[(CapEx + OpEx) - S]}{PV(AEP)} \tag{3}$$

with AEP (see Equation (1)), CapEx and OpEx are considered in Present Values for the expected lifetime of a WEC farm, hence the final LCoE being discounted. AEP is a major parameter that determines the LCoE behaviour. Although, LCoE is an indispensable tool as it provides a level field for technology comparisons, it does not directly dictate the economic viability.

Assessing the feasibility of an investment can be obtained by estimating the detailed cash inflow and outflow, summarised with a Cost-Benefit model [53]. However, for use of a Cost-Benefit model several more parameters have to be defined such as the inflation (g), energy escalation rate (e), annual taxation, etc., in order to obtain more comprehensive and realistic results [54]. In both cases for discounted LCoE (see Equation (3)) and Cost-Benefit modelling, monetary values are adjusted to Present Values (PV) with a discount rate (r) for the lifetime of operation (n), and payback (amortisation) is estimated at the point for which the total revenues (R_n) are greater than total expenses per year (C_n).

A fixed annual cost for maintenance & operations is assigned as a percentage of CapEx, and values are estimated in PV terms. This is the annual fixed cost ($OpEx$), variable (unforeseen) costs (V_{cn}) can be added but in this study they are considered as zero, with total costs expressed per year (C_n).

$$C_n = CapEx + [OpEx \cdot CapEx] \cdot \left[\frac{1+r}{1+i} + \cdots + \left(\frac{1+r}{1+i}\right)^n\right] \tag{4}$$

Revenues are estimated by providing the annual energy (AEP_n), that is sold with an electricity price (c_o), the finalized earnings of each year are adapted to current prices. In this analysis a constant electricity price (c_o) is considered as discussed in Ref. [55].

$$R_n = AEP_n \cdot c_o \cdot \left[\frac{1+e}{1+i} + \cdots + \left(\frac{1+e}{1+i}\right)^n\right] \tag{5}$$

As an analysis case study the Netherlands are taken into consideration, since there is a suitable high spatio-temporal resolution dataset covering 38 years (1980–2017), the North Sea Wave Database (NSWD). The Dutch electricity system supports energy investments by feed-in-premium (FIP) tarrifs (SDE+), which is typically added to the market price [56]. In principle an FIP means the energy producers (usually renewables) receive a top of the spot market price for the electricity production delivered. The FIP can be fixed or variable, and is usually combined with the electricity selling floor or ceiling prices, acting as premium only if market prices are lower than the FIP.

The SDE+ aims to support and strengthen production by renewable energies, eligible technologies are wind, solar, biogas, biomass and hydropower with several sub-divisions that have different FIP. Wind has FIP 5.4–8.5 cent€/kWh depending on type, size and wind speed resource. Solar from 9.9 to 10.6 cent€/kWh depending on scale and hydropower from 9 to 13 cent€/kWh. A type of ocean energy, tidal power is included in the hydropower scheme with the given range. For our analysis the selling price of electricity is assumed as constant and equal with an FIP 10 cent€/kWh.

Energy prices are dependent on consumption patterns, Dutch bidding prices had an increase of 33% from 39.3 €/MWh to 52.5 €/MWh. Similarly, the wholsale prices in Western North Europe have also seen an increase and are between 45 and 55 €/MWh [57,58]. A final component that will affect pricing in electricity, is the Emissions Trading Scheme (ETS). This is part of a long-term scheme based on a capped policy that favours “greener” solutions with increases in emissions market prices, by annual imposing emission restrictions (reducing allowed emissions). Since 2018 CO_2 prices have seen dramatic increase from ≈ 5 €/allowance (Tn) CO_2 (2013 price) to near 25 €/Tn CO_2, a fivefold increase, see Fig. 3. Estimates are expecting the barrier of 35 €/Tn CO_2 to be exceeded soon, and 2030 future values to be ≥ 60 − 80 €/Tn CO_2.

The North Sea is a moderate to high wave energy area, 99th percentile indicated that H_{m0} is ≤ 7 m at Northern parts, furthest from shore, and 99th wave period percentile T_{m10} is ≤ 11 sec. At central parts H_{m0} and T_{m10} percentile values are ≤ 5 m and ≤ 8 s, respectively. Further down, at the English channel H_{m0} is ≈ 50% lower than the highest Northern parts and T_{m10} ≈ 75% less, see Fig. 5. Such values are found further ashore, nearshore regions that are of higher interest for first generation wave farms, have almost uniform values throughout the coastlines.

At the Netherlands close to shore values H_{m0} are 3–4 m, with high frequency periods every 5–6 s, this “uniformity” is due to the fact that Dutch coastlines are predominately exposed to

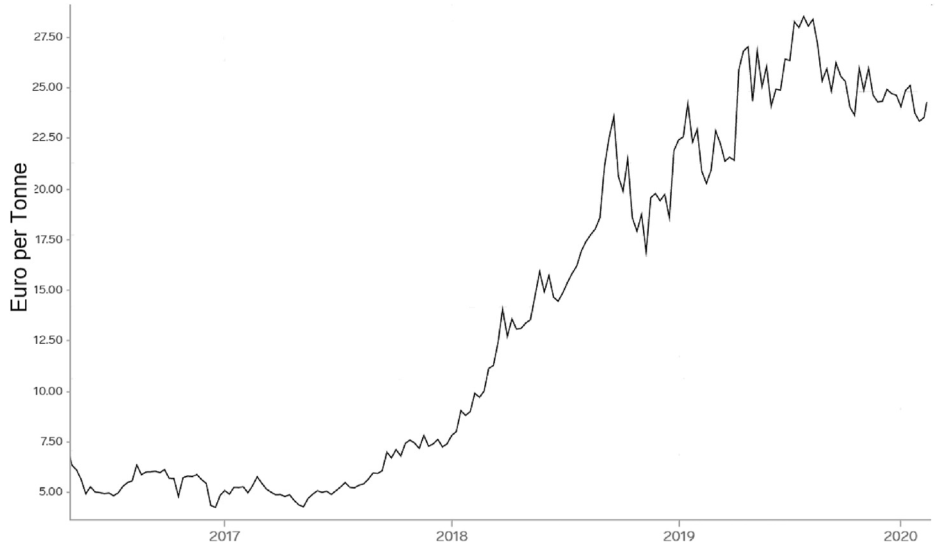


Fig. 3. CO_2 European Emission Allowances (€), showing the evolution of prices during the last 5 years [59].

transformed swells propagating downwards from the Norwegian Sea, with little or no interference of significant land masses or complex bathymetry that can influence the resource, and enhance the occurrence of characteristics such as diffraction. Majority of the wave resource that reaches the coastlines is predominately affected depth friction, and nearshore triad interactions which modify larger wave periods (low frequency) wave-swells, into higher frequency, resulting in reduced H_{m0}. On the other hand, the United Kingdom (UK) has smaller H_{m0} values at latitudes below 52^o though exposed to similar swells, the Norwich area poses an "obstacle" which propagated waves interact with. At latitudes $\geq$ 52^o the British coastlines have larger H_{m0} nearshore values 4–6 m, with longer period waves (T_{m10}) at 8–10 s, with exception the Wash natural reserve gulf, where waves are reduced due to surrounding orography, see Fig. 5.

However, the North Sea whilst is not met with the high swell waves, like the ones at the Atlantic coastlines, i.e Scotland, it shows relatively small variations from its mean, see Fig. 4. Standard deviation of H_{m0} along the Dutch coastlines is from 0.6 to 1.2 m and from 0.2 to 0.6 m at the United Kingdom coasts. T_{m10} standard deviation shows a more distinct separation with the regions $\leq$ 52^o showing identical values $\approx 0.8 - 1$ sec. At latitudes $\geq$ 52^o there is a slight increase in deviation from 1.2 to 1.6 s, both for the United Kingdom and Dutch coastlines, see Fig. 6. Hence, regions with smaller deviation can be more beneficial for a more persistent energy production, as metocean conditions will not vary significantly.

3. Results

Our main focus is to investigate financial WEC feasibility along moderate resources with example the Dutch coastlines, available WECs have been considered with depth limitation of $D \leq$ 30 m. Fig. 7 provides a clear indication for the performance of WECs, the figure uses aggregates the values at all locations and WEC.

Nearshore devices, depend on transformed waves at low depths, where the surge phenomenon is most prevalent, such example is the Bottom Oscillating Flap (BOF1 & BOF2). In turn this means that device size is larger (BOF2), therefore excitation surge forces will require to be higher, BOF2 starts producing at 2 kW/m and reaches its peak value at 291 kW/m, whilst the smaller BOF1 needs 0.6 kW/m to start operation and reaches its nominal value at 123 kW/m. Of course at such depths the wave energy content is not as high all the time. BOF1 achieves 50% of its nominal capacity at 14.6 kW/m (H_{m0} $\approx$2.5 m), while the larger (BOF2) obtains same 50% P_o value at 63.7 kW/m (H_{m0} $\approx$4.5 m).

As per Fig. 5, at shallower waters 99^{th} percentiles are consistently $\leq$ 5.5 meters, with small deviations predominately occurring at the Wadden islands ($53 - 53.5^o$ N–$4.5 - 5^o$ W). Their performance, both max and mean, has also a difference of about half, with the best of BOF1 53.6% at 52^o N - 4.5^o W and BOF2 22% at 52.3^o N - 4.5^o W, with their means at 25% and 11.5% respectively (see Fig. 7).

Nearshore and deeper WECs, are less influenced by shallow water dynamics, depending more on principal of operation and WEC size (see Table 1). Remainder devices are a mixture of different technologies predominately attenuators and heave buoys, with small variations in their size, power-take-off (PTO) and placement along the datum (submerged, floating, etc.). The optimal mean CF attained by the attenuator (OceanTech) is 24%, followed by a point absorber 22.3% (Wavestar), lowest maxima are observed by an overtopping 5.4% (Wavedragon).

Highest CFs are OceanTech: 47.1%, Wavestar: 30.9% and BOF 1 with 53%. However, mean behaviour across the domain does not reveal the same selection, the highest WECs are reduced to $\approx 22 -$ 25% a reduction of almost 50% by their maxima. OceanTech and Wavestar, are devices with nominal capacities 600 kW and 500 kW, both reaching peak production at $\approx 16 kW/m$. Larger devices (high nominal capacity) usually depend on swell dominated seas, however, their design is often not accounting for reduction in the occurrences probabilities due to climate patterns. Issues of production availability have been previously raised [22,60], concluding that most of the time swell dependent devices cannot operate due to the low percentage of conditions they need within a year. With moderate metocean condition being more prevalent, and can therefore benefit WEC operation.

Spatial distribution of most efficient WECs is given in Fig. 8, which complements the aforementioned results and indicates that no one WEC can obtain its highest across the whole region. A double criterion has been applied that considered both depth applicability and distance from the nearest shoreline Fig. 8 panel (c). In subpanel (a) of Fig. 8, OceanTech exhibits better performance at latitudes between $52 - 55^o$, while closer to the English channel expected performance drops by 75%. A swell favourable device ($T_{m10} = 11$ sec) is not suitable for the moderate conditions, and

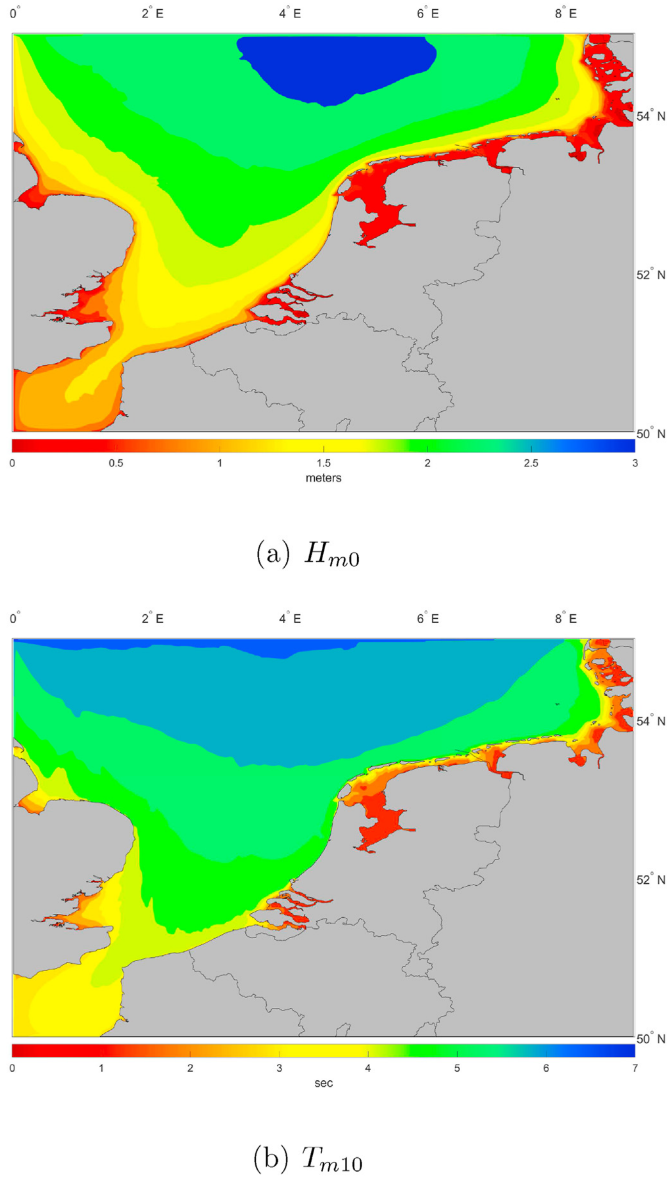


Fig. 4. Mean metocean characteristics at the North Sea for H_{m0} in meters and T_{m10} in seconds. Statistical conditions are based on 38 years from the NSWD.

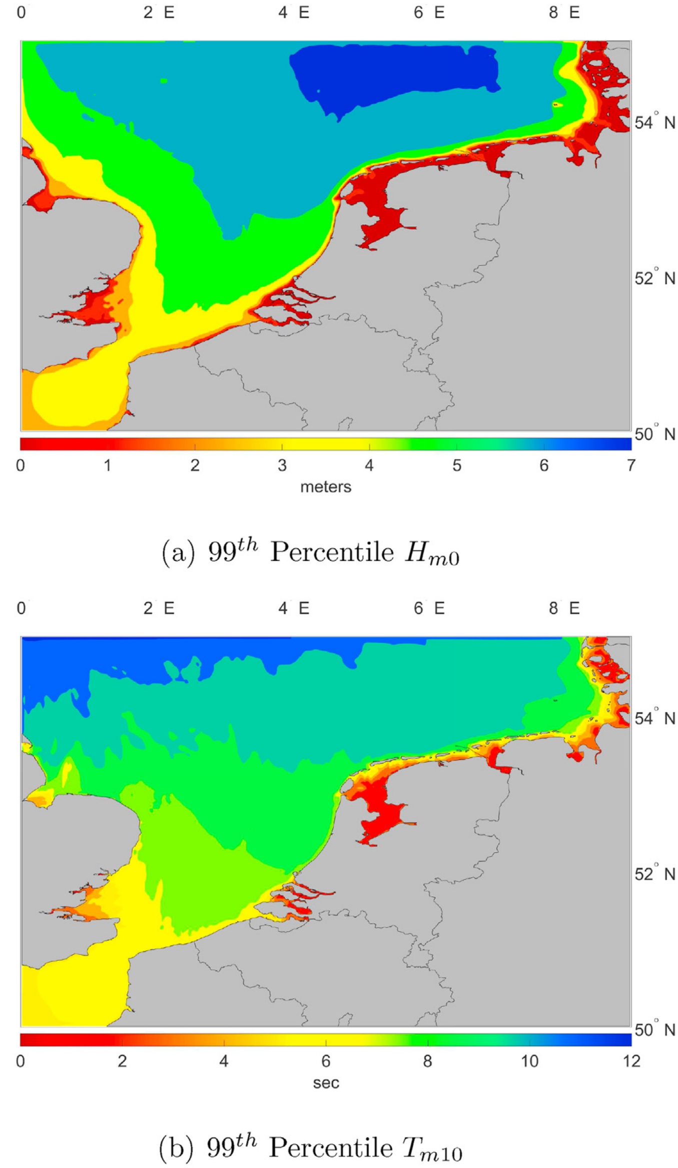


Fig. 5. Quantitative metocean characteristics at the North Sea 99^{th} percentiles values for H_{m0} in meters and T_{m10} in seconds. Statistical conditions are based on 38 years from the NSWD.

although it availability is high its maxima are seldom obtained, therefore its capacity factors are well below the 10% region. Subsequently, the optimal CFs across the domain was plotted to indicate the regions of which a the best CF can be obtained, see Figs. 9–10.

3.1. Economics

Data necessary for economic analysis are divided in two main parts: (i) device costs and (ii) revenue potential. Firstly, focus is given on major WEC economics aspects, which are comprised by CapEx and OpEx. It has to be noted, each device has different subdivisions and requirements, depending on WEC type [40,61]. However, this analysis is mostly concerned on the economic performance of the potential wave farms and not the effects on individual components, for that the reader is refereed to de Andres et al. [40].

The OpEx is dependent on CapEx values with a range from 8 to 15% [62], depending on device and location similar to offshore wind [25]. For OpEx considerations we abide by the definitions found in Babarit et al. [63] and do not model un-expected costs (i.e. “unique” failures of equipment). The ranges obtained align with the suggestions in several studies [35,39,40].

For the sensitivity analysis of the revenue potential two main parameters parameters were considered, which have an effect on LCoE values, CapEx and discount rates. Power production is also a vital, but in our analysis the power performance has been in-depth estimated and “optimally” analysed through use of NSWD, which allows us to estimate highly realistic expected AEP. The discount rates used represent (i) a social discount rate value (r: 5%) (ii) conventional to high risk investment rate (r: 10%). A social discount rate is used for projects that are expensive, but can provide significant added value to societies, with relevant marginal societal benefits. Such projects often address pressing issues such as environmental protection, reduction of emission, local employment, increase in standard of living, health benefits, etc. In a recent

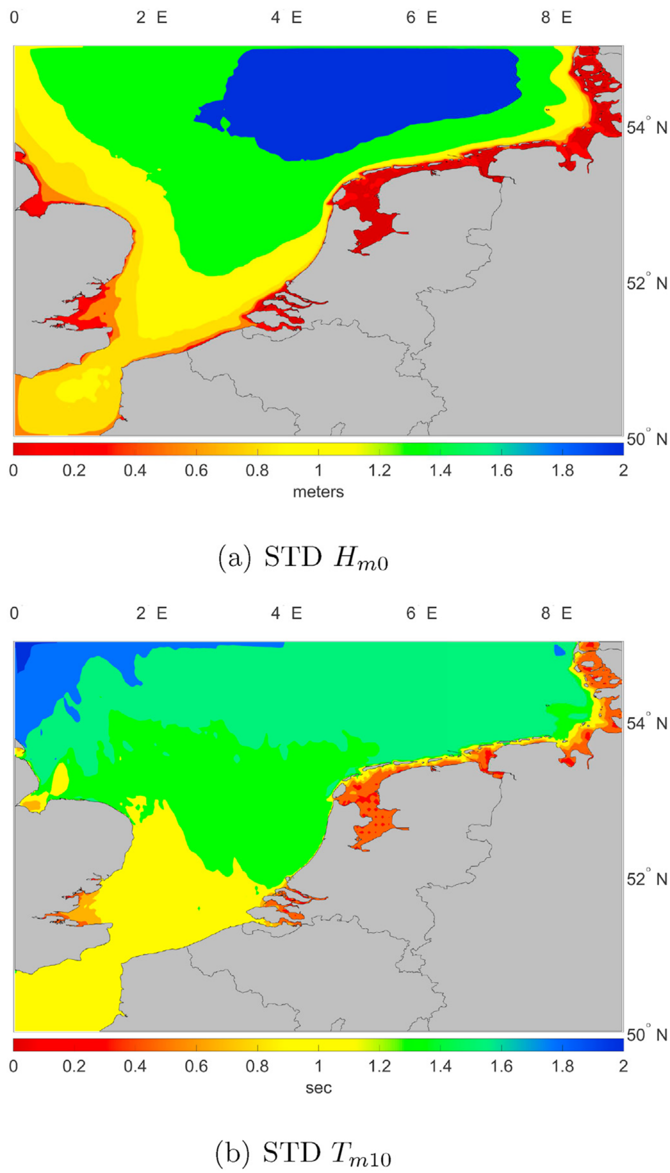


Fig. 6. Quantitative metocean characteristics at the North Sea standard deviation (STD), for H_{m0} in meters and T_{m10} in seconds. Statistical conditions are based on 38 years from the NSWD.

estimation the Netherlands Environmental Assessment Agency (PBL) assessed discount rates, for most renewables, and mature technologies obtain values from ≈ 1.5–4% [64], hence assumption of our discount rates can cover all possible optimistic/pessimistic scenarios.

For the detailed amortisation analysis, a selling price of electricity (c_o) has to assumed, that combines the FIP SDE + price combined with the potential avoided CO_2 emissions, with emission intensity (Tn/MWh) based on the U.S. Environmental Protection Agency Greenhouse Gases Equivalences methodology [65]. Arguably, with the decarbonisation of energy sector the benefits to societies by wave energy include reduction of emissions, local jobs growth, better environmental quality, and reduced of health issues associated to energy [53,66–68]. The assumptions for our economic evaluation are given in Table 2.

The differences between LCoE are significant, and that indicates the high dependence and sensitivity of LCoE on power production. If the location selected is not suitable, then the economic viability can be severely hindered, between CF_{mean} and CF_{max} large differences occur for BOF1: 52%, followed by OceanTech: 49% and Wavestar: 27.5%, underpinning the importance of WEC selected for a location, and their dependence on climate conditions. In all instances, and for all possible techno-economic LCoE configurations based on CF_{max}, the LCoE is smaller for any discount rate. Lower variation is achieved by the BOF 1, however, it is noticeable that CapEx changes have greater effects of the WaveStar range. When a mean value is used then the CapEx sensitivity is higher, leading for greater differences between upper and lower bounds, see Fig. 11.

4. Discussion

The suitability of WECs are based solely on power basis, however, the top three converters also are in line with the findings in Ref. [31], where a detailed comprehensive index was used accounting also for climate variations and extremes. The findings corroborate that OceanTech and Wavestar are favourable in nearshore water, shallow waters optimal is BOF 1. For moderate resource devices should be acquire their maximum output in regions of $H_{m0} - T_{m10} \leq 5$ meters–8 secs.

Although, NSWD covers majority of the North Sea we have considered only regions that are ≤ 30 m in depth and are relatively close from the shore, therefore the effective available space represented ≈ 27.2% of the domain, OceanTech represents 20.4%, Wavestar 2.7%, and BOF1 4%. Although, an North Sea advantage as a continental Shelf Sea, is that depths are quite small and without large gradients. In this case the distance from shore is also considered as a limiting factor, with furthest point at 100 Km, but can benefit from the expected offshore wind farm developments, sharing cabling cost since it is anticipated that the North Sea will experience a boon in offshore wind installations.

Comparatively, some of these devices have also been simulated to higher energetic environments, where device that in the North Sea underperformed were superior at higher energy conditions. Locations off the coast of Scotland and Norway showed that the WaveDragon is amongst the best performing devices for long swells, with CF from 35 to 45% and highest 65%. Devices such as WaveStar had significant less performance from 10 to 15%, and the Pelamis was from ≈ 18–30%, with highest 47% [69–72]. This reaffirms the fact that not all devices are globally applicable without proper adjustments.

The size of each device can also assist in estimating, the packing factor per WEC within a 1 km^2 spatial area. The packing factor considered within this study can be representative and is used only to establish what is the feasibility of a wave farm in terms of MW. Spacing both in terms of latitude and longitude as well as the packing order, will have serious and possible detrimental effects on the performance of an array depending on type of WEC.

Gunn et al. [73] simulated the Pelamis considering a packing density of 5 per Km with next line being 400 m apart, i.e. ≈11.5 MW/Km^2. Veigas et al. [74] came to similar packing density along longitudes, with a single row of WEC lengthwise and with latitudinal spacing of 100 m, achieving a higher density factor but without indicating technology. Bozzi et al. [75] performed a variable sensitivity analysis on the design parameters for a WEC farm, based on a circular design with varied diameter geometry (D), and distance according to 5D-10D-20D-30D alongside different angles of attack by the wavefront, pending on approximate WEC capacity can be from $\approx 10 - 100 MW/Km^2$. Delgado et al. [76], used also a specific WEC long-spun WEC with 90 m length (L) and packed at different spacings (2 L,3 L,4 L), and pending on installed capacity this can have $\approx 20 - 40 MW/Km^2$.

With regards to the selected WEC there can be positive or negative WEC array effects, either by improving energy production

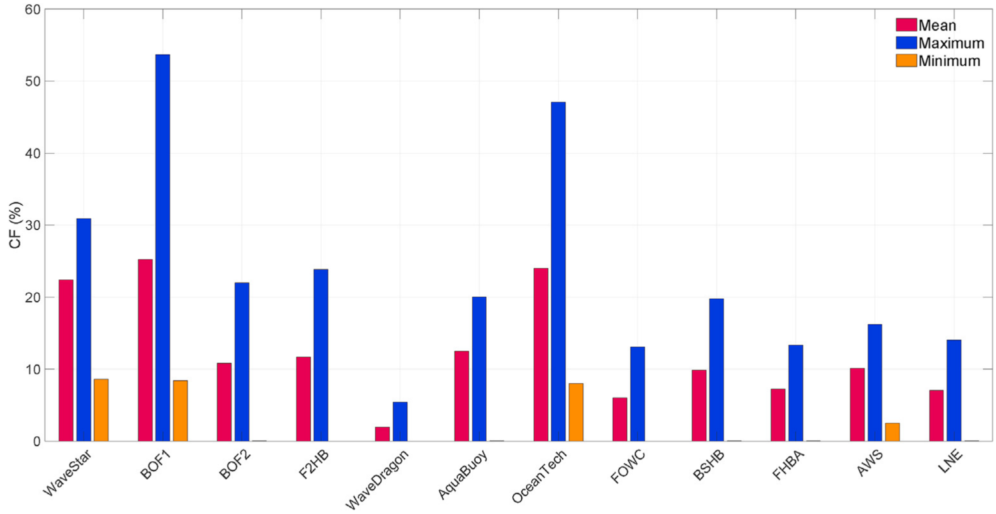


Fig. 7. Domain aggregated CF performance of the device, for all grid points within the domain and allowed depth. Near-zero values are not visible due to scale, depth applicability for $10 \leq D \leq 30$.

instead of reducing it [77]. This is subjective and has to be analysed with further higher resolution time frequency domain models, after a suitable location is selected. Therefore with regards to feasibility of a wave farm, and keeping in mind the optimal power production. One can safely assume a feasible packing density within is 10– 20 MW/Km^2. Henceforth, for the economic analysis we have considered a 10 MW wave farm as feasible per grid cell (although our resolution is $\approx 2\ Km^2$), which also represent expected capacity factor. Comparatively, modern wind turbines can accommodate 5–8 MW/Km^2 [78].

The potential for wave energy is assessed both for LCoE and payback. Unlike studies that use only point data relying on expert advise, which may carry biases. The selected WECs were tested along all available locations, the final top selection was also corroborated by the use of an un-bias index (SIWED), which quantifies the site suitability of a site based on energy variability, extreme events necessary for economic considerations and energy production. In both cases the best WEC for the regions are the same, and are represented by moderate operative converters [31].

In terms of economic viability, the relationship between power performance and CapEX, regardless of discount rate, exclude as viable the WECs over ≤ 4.5 M€/MW. Devices with CF ≤ 30% are potentially viable, but only when social rates are taken into account. WECs that follow a "production-to-resource" approach obtain the highest potential using near CF_{max}, as they are highly viable regardless discount rate. On the contrary, as expected, a high-risk discount rate (r : 10%) with CapEx ≤ 3.5 M€/MW and CF ≥ 40% is viable throughout, with an increase in CF allows for significant CapEx reductions ≈ every 500 thousand € of decrease. Although, CF ≤ 20% are not viable under any condition for a discount rate of 10% and above, see Fig. 12.

The analysis estimated payback based on the different CapEx, CFs and discount rates, providing amortisation periods for all different cases. It is important to highlight that the following two assumptions are made (i) the CF are within a range of 20–50% as these values are the mean and max of the analysis (ii) due to the specificity of each WEC and the different components required CapEx is also considered representative. The specifics of each technology can be "broken" down further, however, this analysis offers the viable pairs of CapEx-discount rate-CF and corresponding LCoE that can be considered viable, see Fig. 12. Table 3 estimates the LCoE and counts the options which have a positive amortisation. The range of LCoE is from ≈ 60 €/MWh for the high CF of BOF1 with a social discount rate, with mean CF of the same WEC for similar CapEX being 45% higher (131.2 €/MWh). The results are expected to be valid for similar resource regions globally, as WECs performance will follow similar expectations.

Depending on "viable" couples this is also reflected in the spatial LCoE, when CapEx is ≤ 1.5 M€/MW and a WEC is optimally selected, values range from 60 to 350 €/MWh, see Fig. 13. For a social discount rate LCoE values are from ≈90 – 180 €/MWh, with a small portion of Northern Dutch coastal shallower locations having ≤ 90 €/MWh. Increasing the discount rate, but retaining the same CapEx and CF performance, LCoE increases to majority of the central region from ≈160 – 240 €/MWh. Finally, when the discount rate considers the investment as high risk, the LCoE is from ≈ 140 – 280 €/MWh.

WEC have their economic attractiveness reduced for CapEx values ≥ 4.5 M€/MW for r: 5%, and ≥ 3 M€/MW for r: 10%, see Fig. 14. In such instances LCoE increase, reaches ranges of ≈300 – 650 €/MWh, ≈250 – 500 €/MWh, and ≈350 – 500 €/MWh for CapEx 4.5, 3 and 2.4 M€/MW, respectively. These results show the shift of viable CapEx-CF, which clearly shows that as CF increases the CapEx can be marginally higher.

This leads to the suggestion that WEC size and conditions "matching", matters more than name plate capacity, it has also to be clearly underlined that the monetary values discussed are based on pre-commercial devices, with highest ranges corresponding from literature and attributed to higher energetic environments.

Even in this case, if the converters are placed according to a "resource-to-production" methodology it can achieve low LCoEs, that can be the starting point for deployments and further capital reductions. However, the analysis clearly shows that wave energy sector, is a high capital intensive but with several societal benefits

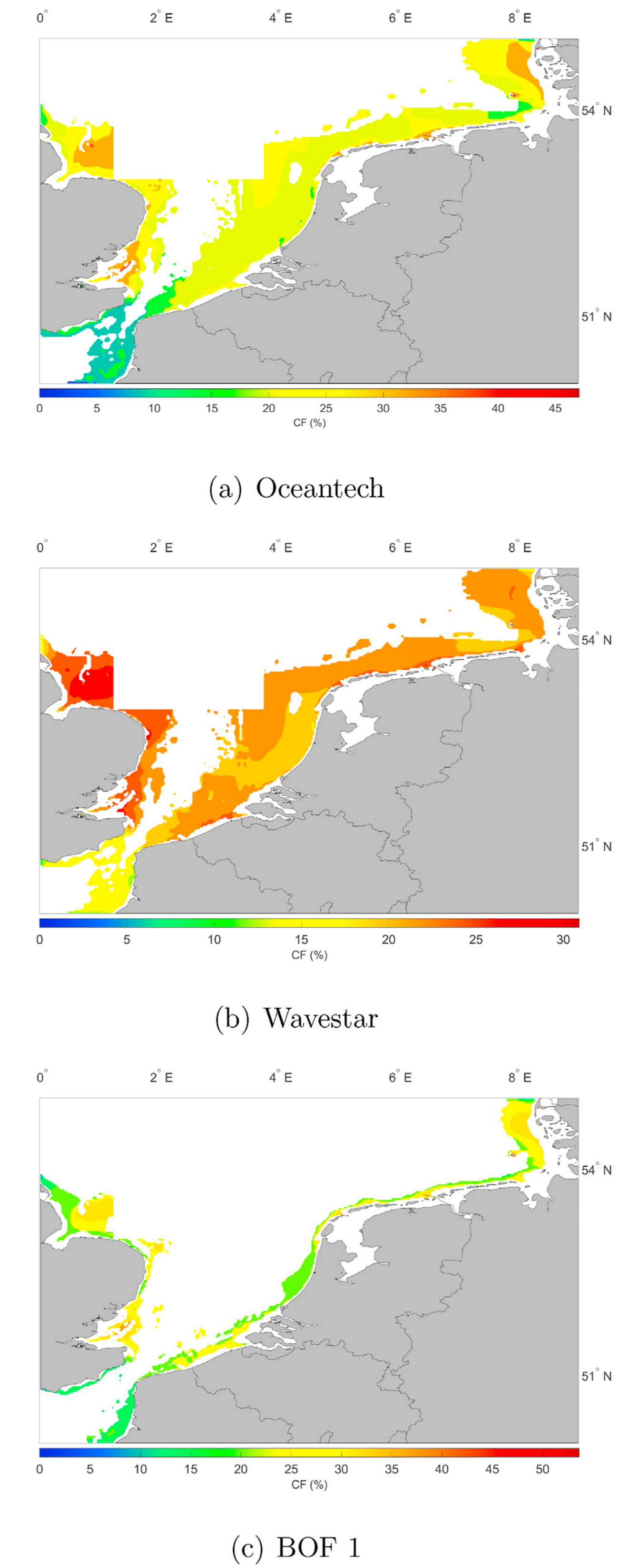


Fig. 8. Domain performance of two WECs as analysed by Fig. 7, based on spatially for $10 \leq D \leq 30$, exception is the BOF 1 which is applicable only at depths $\leq$ 10 m.

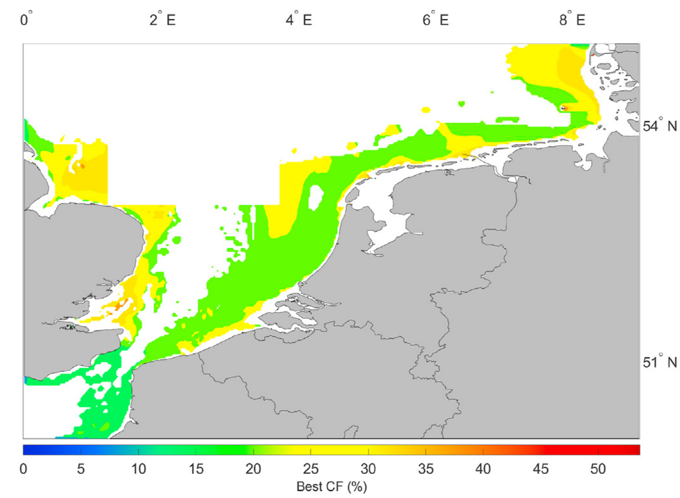


Fig. 9. Spatial representation of the optimal CF that was estimated for the domain, all devices have been considered with depth applicable limitations ($10 \leq d \leq 30$ m), and respective distance from shore $\leq$ 100 km.

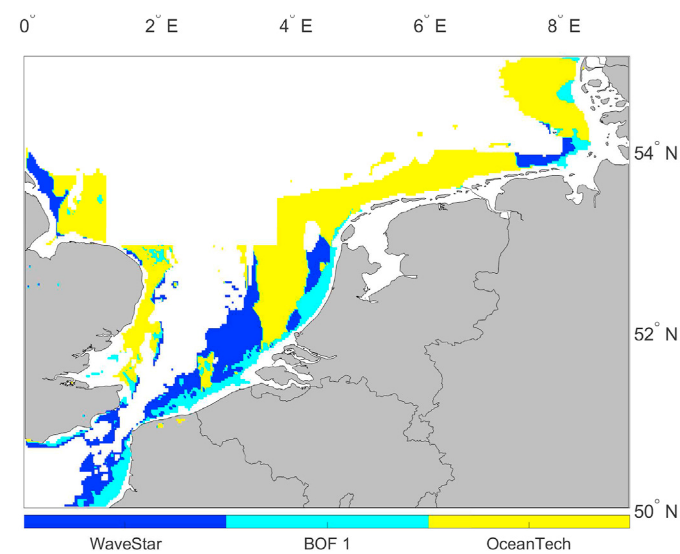
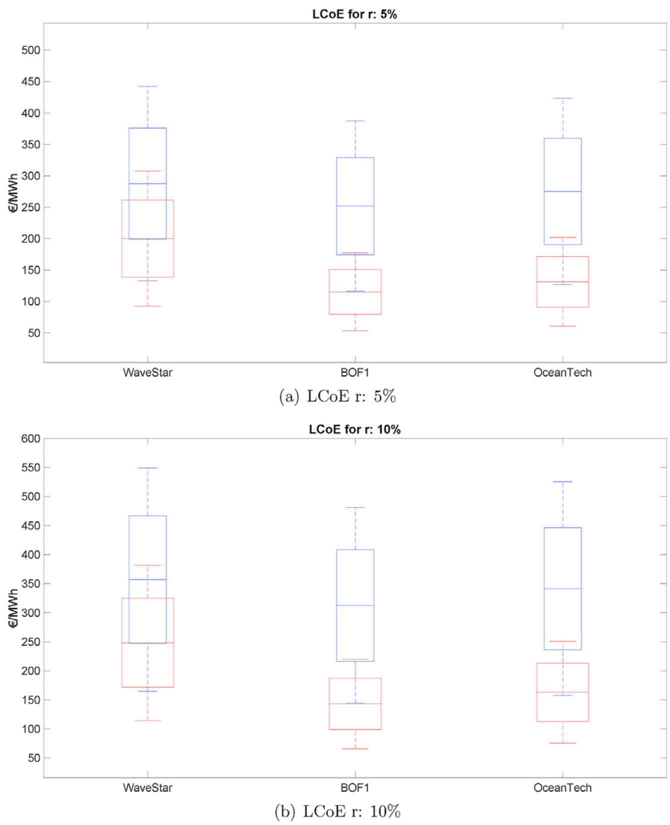


Fig. 10. Spatial representation of the optimal three CF per WEC as estimated for the domain.

Table 2
Assumptions made on the economic modelling.

CapEx	1.5–5 m€/MW (500 k/incr.)	
OpEx [35,39,40,63]	8%	
Discount rate (r) [64]	5% (social)	10%
Project Lifetime	20 years	
$SDE+$ [56]	100 €/MWh	
CO_2	35 €/Tn	
c_o	CO_2 + SDE+	

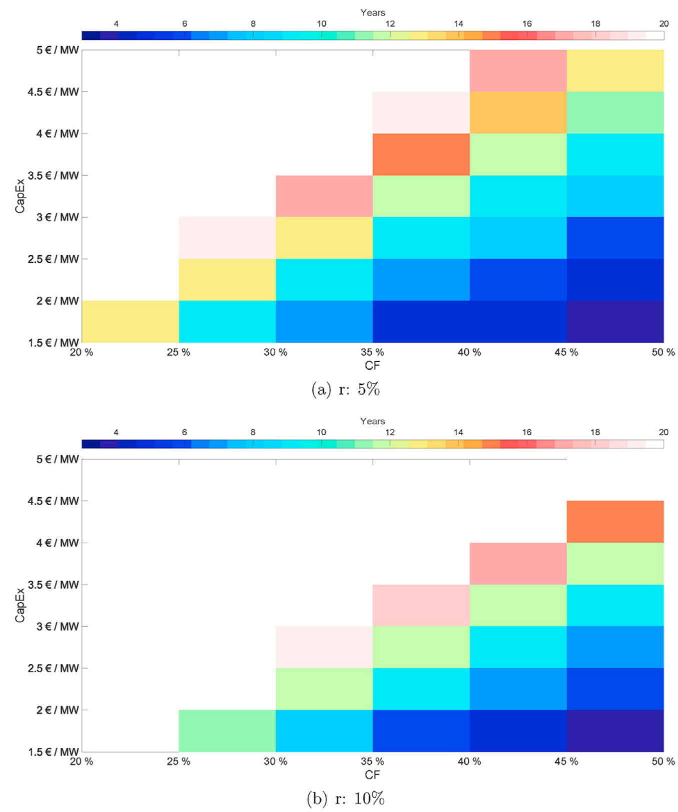
that often times are overlooked. Therefore, investments with discount rates over 10% will jeopardise the viability of capital payback, and also lead to higher LCoE.



(a) LCoE r: 5%

(b) LCoE r: 10%

Fig. 11. LCoE for different discount rates, the red box represent the best/optimal selected device (max CF) and the blue box represent the mean CF of each WEC.



(a) r: 5%

(b) r: 10%

Fig. 12. Amortisation periods expressed in years for the different scenarios as presented in Table 2.

5. Conclusions

At shallower regions, surge devices with similar operating principles like BOF1 appear more favourable, at "deeper" regions two most prevalent devices are OceanTech and WaveStar. Interestingly they showcase distinct regions of applicability, with an almost inverse distribution. In Fig. 8 OceanTech is most favourable in the upper regions of the North Sea (swell dominated), however, regions where WEC efficiency drops (swell transformation) are substituted by Wavestar with CF values similar to the ones encountered in upper latitudes.

In terms of LCoE most studies so far classified the North Sea and other moderate resource as non-viable, however, this analysis clearly shows that by utilising a comprehensive methodology, LCoE can attain low value as 60 €/MWh. For average CF values there is a larger dispersion of LCoE with upper and lower bounds (CapEx dependence), regardless of discount rate used, with 55% upper and lower bound differences. When the energy performance is optimised either by device or location selected, then the variation between upper and lower bounds are reduced to 25–30%.

High energy environments, require much more capital to be utilised, to ensure survivability as probability of extreme conditions occurring is increased. Indicatively, extreme return wave differences for survivability between the most energetic wave locations in Scotland, Brittany (France), and the Aegean can be 3–5 times less [79,80]. Therefore most probable CapEx requirements for 1^{st} TRL 7 devices suitable for milder environments, should be considered realistic between 2 and 3.5 M€/MW for social discount rates when a 25–35% CF is recorded, and ≤ 2.5 M€/MW for a high risk (r: 10%).

The results clearly indicate the potential of some devices to benefit by learning rate reductions [35,40,67] and reduce their LCoE closer to 10 cents €/kWh in the next 10 years, if proper support and development methodologies are followed moving closer and even surpassing expectations of the wave energy industry. The sensitivity analysis of the costs in this study can ensure that all possible configurations have been explored and the results are applicable for first generation devices, up to possible 2030 cost that will have benefited by economies of scale.

CRediT authorship contribution statement

George Lavidas: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing - review & editing, Writing - original draft. **Kornelis Blok:** Conceptualization, Validation, Writing - review & editing.

Declaration of competing interest

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

Table 3
LCoE €/MWh based on different discount rates, CapEx and performance (as estimated in Fig. 7).

	Mean CF					
	r: 5%			r: 10%		
CapEx (Million €/MW)	Wavestar	BOF1	OceanTech	Wavestar	BOF1	OceanTech
1.5	149.9	131.3	143.4	182.6	159.8	174.6
2	199.9	175.0	191.3	243.4	213.1	232.8
2.5	249.9	218.8	239.1	304.3	266.4	291.1
3	299.9	262.5	286.9	365.1	319.6	349.3
3.5	349.9	306.3	334.7	426.0	372.9	407.5
4	399.9	350.0	382.5	486.8	426.2	465.7
4.5	449.8	393.8	430.3	547.7	479.4	523.9
5	499.8	437.6	478.1	608.5	532.7	582.1
	Max CF					
	r: 5%			r: 10%		
CapEx (Million €/MW)	Wavestar	BOF1	OceanTech	Wavestar	BOF1	OceanTech
1.5	104.2	60.1	68.4	126.9	73.1	83.3
2	139.0	80.1	91.3	169.2	97.5	111.1
2.5	173.7	100.1	114.1	211.5	121.9	138.9
3	208.5	120.2	136.9	253.8	146.3	166.7
3.5	243.2	140.2	159.7	296.1	170.7	194.4
4	278.0	160.2	182.5	338.4	195.0	222.2
4.5	312.7	180.2	205.3	380.7	219.4	250.0
5	347.5	200.3	228.1	423.0	243.8	277.8

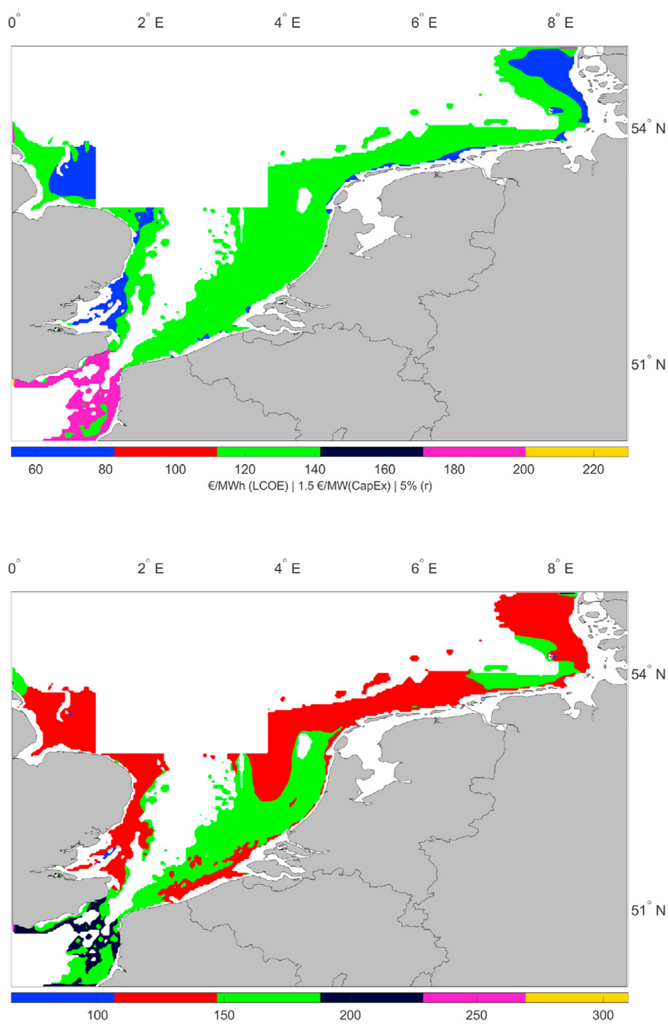


Fig. 13. LCoE spatial distribution for different conditions, the energy performance as estimated in Fig. 9 and CapEx 1.5 m€/MW.

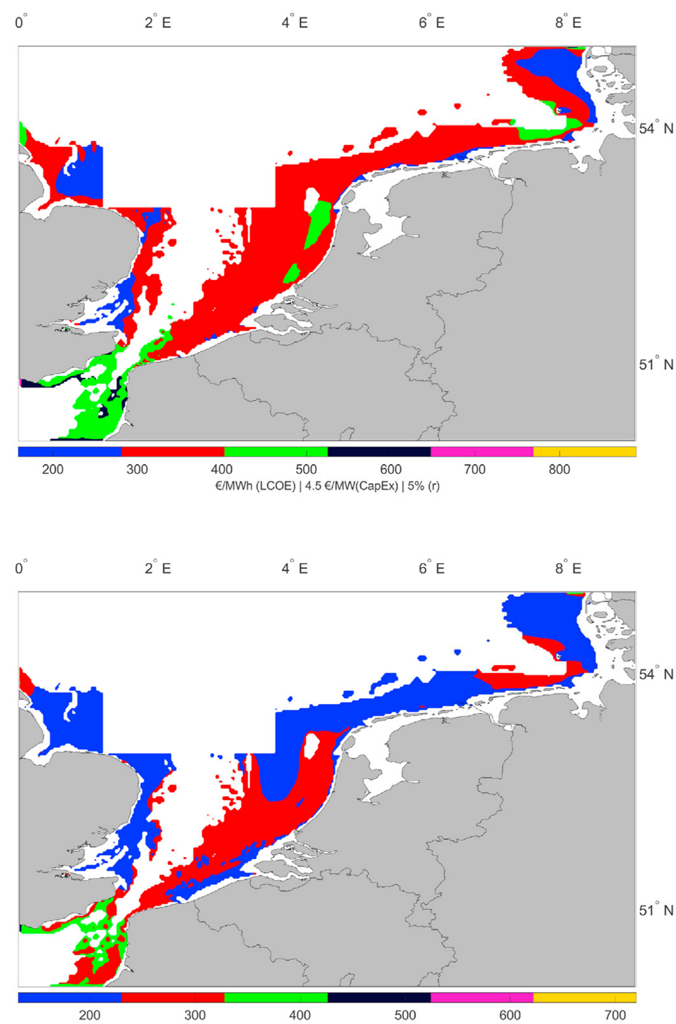


Fig. 14. LCoE spatial distribution for different conditions, the energy performance as estimated in Fig. 9 and CapEx varies according to the threshold that makes it viable as presented in Fig. 12 and Table 3.

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