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Levelised Cost of Electricity for wave energy converters and the perception of milder resource non-viability in the North Sea

George Lavidas, Kornelis Blok

Abstract—**Wave energy is one of the most dense, predictable, and persistent energy sources, that has gone under-utilised, with many countries exposed to it. Depending on orientation with regards of coastal fronts to swells, resources can be characterised as high, moderate, and low. Wave energy can provide significant benefits as renewables acquire more share in the electricity production. So far focus for the development of wave energy is given to areas with resources over 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 explores whether mild resource can be cost-effectively exploited, by properly attributing a "production-to-resource" approach. The main question answered is whether mild resources are viable for wave energy. This premise is often dismissed, without much consideration or evidenced arguments. In terms of wave energy production potential, the wave density potential (kW/m) is not the determining factor. Results aim to realistically assess the potential and alter the perception of non-viability for wave energy converters. Our study examines the evolution of LCoE at various locations in the North Sea and also tries to assess different impacts of external factors at the financial viability of wave energy farms.**

Index Terms—**LCoE, North Sea, Energy economics**

I. Introduction

The 2015 Paris Agreement set ambitious plans to curb the catastrophic effects of Climate Change [1]. The European Commission (EC) 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 as its major focus. Amongst the aims is for Europe to maintain leadership, whilst moving to a free or near neutral energy system. The EC is committed to achieve the Paris Accord, translating this into tangible 2030 targets: reduction $\geq$ 40% greenhouse gas emissions,$\geq$ 32.5 % for share of renewables in the electricity system, and $\geq$ 21.5% energy efficiency. The EC has set ambitious targets to reduce GHG emission by $\geq$ 55% and increase renewable energy by $\geq$ 32%. These will not be achievable without tapping into the vast and unused offshore renewable energy potential that includes wind and ocean energies. In the EC offshore energy strategy it is expected that at least 1 GW of ocean energies will be deployed by 2030, with a view for at least 40 GW by 2050 [4].

These ambitious targets are reflected into the National and Energy Climate Plan (NECP) of most Member States, for example the Netherlands aims to have a $\geq$ 49% reduction in GHG and $\geq$ 27% of renewables by 2030, while in 2050 the goal is for 100% renewable energy generation and 95% GHG reduction. Such ambitious goals require large deployment of renewables and the utilisation of all indigenous resources. Given the land scarcity and the spatial footprint of onshore renewable energies, the untapped potential of offshore locations is essential to achieve the government targets. 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 [5], [6]. 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 [5].

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 estimated at global [7] and local level [8], with hourly and sub-hourly estimations of renewable energy production, indicate that multi-renewable generation offers significant advantages in reducing the variability, especially at systems that highly depend on wind and solar [9]–[11], and in the long-term energy costs are decreased [12], [13]. Multi-generation of renewable energies can also address other issues such as water scarcity, through desalination [14].

Wave energy is one of the most dense, predictable and persistent energy sources, that has gone under-utilised [15], 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 [16]. Fairley et al. [17] assessed the global resource, and underlined the similarity of wave period values be-

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tween 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 [18], predominately at deeper ocean regions where converters are not deployable. 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 [19]. Metocean condition at European coastlines high latitudes have increased [20], while the Mediterranean Basin shows a higher stability with smaller variations [21]. Kamranzad et al. [22], [23] used a Climate Stability Index to assess the Southern Indian Ocean from 1979-2003 and a forecast from 2075-2099. 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 low variability areas as most suitable [17], [24], [25], 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 [26]–[28]. Such optimisations in control strategies can differ per converter type, but they can increase power production from 20-45% [29]. Lavidas [30] introduced a methodology to select wave converts that account for energy production, resource variability and survivability using high fidelity hindcast data from 1980-2017, 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 a high potential contribution of wave energy systems, there are still significant obstacles in accelerating their deployment, predominately associated with energy costs [31]. Initial studies estimated the cost (in Million €) per installed MW (M€/MW) from 3-10 M€/MW [32], [33], 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 [34], with more specific cost data analysed.

Encouragingly monetary requirements have reduced, within a range of 2-6 M€/MW, dependent on device and infrastructure works needed [35], [36]. The Levelised Cost of Energy (LCoE) reported has a range of values from $\approx$ 120-500 €/MWh [24], [37]–[39], underlying the uncertainties which are dependent on device, resource and assumptions. De Andres et al. [36] discussed the ranges for capital and LCoE with a target price at 0.15 £/kWh. Several devices were considered and costs from $\approx$ 2 M€/MW to $\approx$ 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, with out much consideration or evidenced arguments. In terms of wave energy 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. In this study we assess a variety of costs and concluded if done correctly, 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. 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.

II. Materials & Methods

All devices used in the study can be found in [30], the energy production capabilities are estimated by Annual Energy Production (AEP) and the capacity factor (CF) CF. 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 AEP. 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.

Metocean information necessary to estimate the power production capabilities are provided by the North Sea Wave Database (NSWD) with duration from 1980 to 2017 (end of), the calibration and validation of the database can be found in [40] (https://cordis.europa.eu/project/id/787344).

TABLE I
WECs CONSIDERED FOR APPLICATION IN THE DOMAIN, WITH PA: POINT ABSORBER, S: SURGE, AT: ATTENUATOR, OWC: OSCILLATING WATER COLUMN, OT: OVERTOPPING

Name	Type	Directional Influence
WaveStar (600 kW)	PA	Weak
F2HB (1000 kW)	PA	Weak
AquaBuoy (250 kW)	PA	Moderate
AWS (2470 kW)	PA	Weak
BSHB (260 kW)	PA	Weak
FHBA (3619 kW)	PA	Weak
BOF 1 (290 kW)	S	Strong
BOF 2 (3332 kW)	S	Strong
Langlee (1665 kW)	S	Moderate
OceanTech (500 kW)	AT	Strong
FOWC (2880 kW)	OWC	Moderate
WaveDragon (7000 kW)	OT	Weak

LCoE is a metric often used in energy comparisons with Technology Readiness Levels (TRL) [41]. LCoE can carry inherit flaws based on assumptions around economic indices and most importantly AEP, often based on single or limited ($\leq$ 10) years which are highly flawed. This is the reason why many researchers, groups and organisation proposed $\geq$ 10 years for reliable LCoE assessment [42], [43].

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

$$CF = \frac{AEP}{P_o \cdot \Delta T} \qquad (2)$$

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 coordinates (i,j), and ΔT being the time duration for the gathered probabilities.

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

with 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.

Power production is a vital component that in our analysis the energy performance has been in-depth estimated and "optimally" analysed through 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%) (iii) a non-favourable extremely high risk investment rate (r: 15%).

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 estimation the Netherlands Environmental Assessment Agency (PBL) assessed discount rates for most renewables, mature technologies obtain values from $\approx$ 1.5-4% [44], hence assumption of our discount rates can cover all possible optimistic/pessimistic scenarios for developing first generation wave energy farms. Capital expenditure (CapEx) consider values from 1-5 Million €, Operational expenditure (OpEx) is set at 8% of CapEx, and expected lifetime of a WEC farm is 20 years. These ranges have been showed to provide near viable business plans for WEC farms, under specific plans [45].

III. RESULTS

This study focuses in the North Sea region encompassing the Exclusive Economic Zones (EEZ) of The Netherlands, Belgium, Germany and the Northern coastlines of France (see Figure 1). Through the active locations all WECs have been implemented and their long-term power production potential was assessed, considering one device per type of WEC installed.

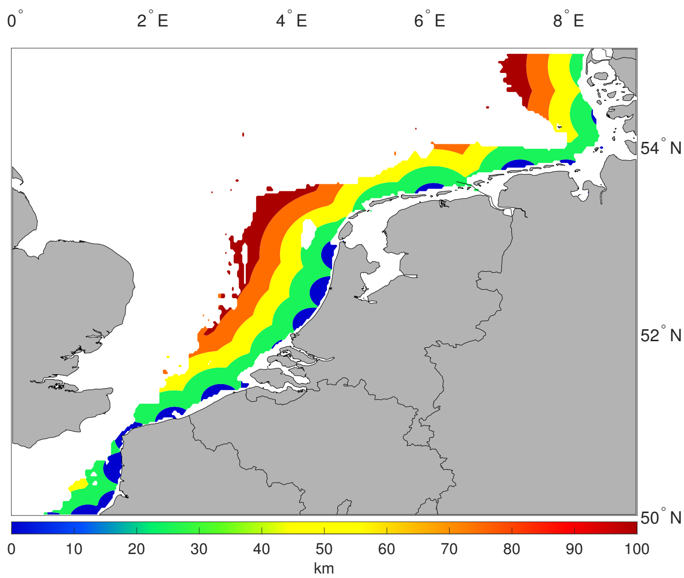

Fig. 1. Active grid points considered in the study, with a limiter the distance from shore being $\leq$ 100 Km from nearest land location.

The wave energy potential in the North Sea region can be characterised as moderate. In the upper latitudes of the North Sea at latitudes above 53.5^o the mean wave energy resource is $\geq$ 16 kW/m. Moving southwards (53.5^o-51.5^o) the potential is from 8-14 kW/m, regions below aforementioned latitudes are from 4-6 kW/m (see Figure 2). As we move towards the nearshore and shallow zones most EEZs ($\leq$ 15 Km distance), due to wave depth transformations because they have similar magnitude of 5-10 kW/m.

The variety of WECs offer diverse solution for different environments, the availability of production [21] is a factor that can affect WEC selection. Figure 3 presents the accomplished ranges for all active domain locations. In the region there are several locations/region

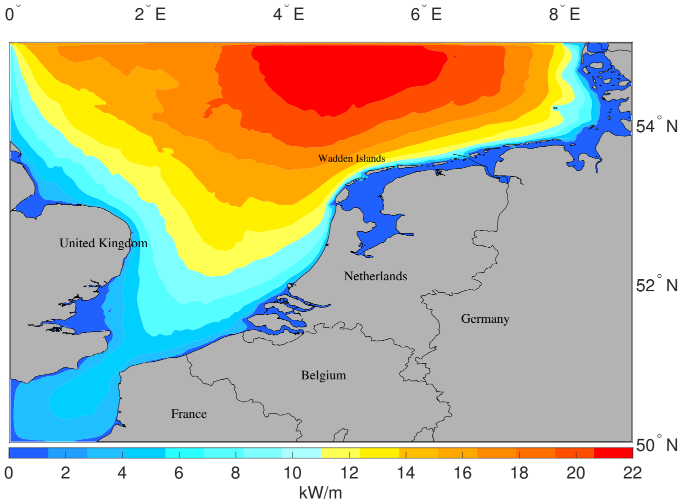

Fig. 2. Wave energy flux in the North Sea region, the dataset is based on North Sea Wave Database (NSWD) presented in [40], spanning from 1980-2017.

that have capacity factor values $\geq$ 30% and are represented by all types of devices, which indicate diverse technology applicability (see Figure 3). High name plate WEC are not as efficient, since moderate resources do not offer wave conditions were they can produce at their maxima, and often operate sub-optimally ($\leq$ 30% of nominal capacity).

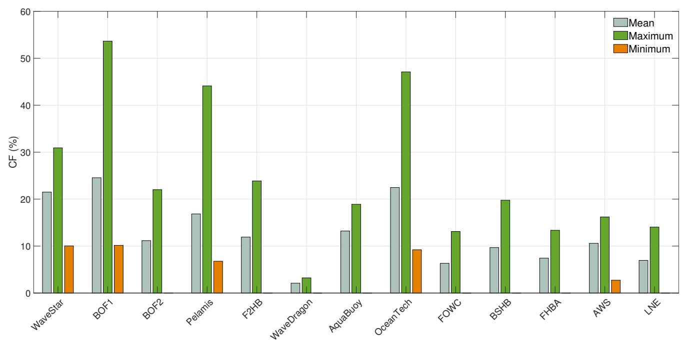

Fig. 3. Power performance indicator for all WEC devices, spanning from 1980-2017.

All available WECs were assessed and for each domain location only the three "optimal" performing device were retained. It has to be noted the estimation directionality has not been taken into account, as such information are not provided for the converters, there are several WECs that are omni-directional (i.e. F2HB), but also several that depend highly on propagating wave direction (i.e. BOF). Hence, some deviation from directional dependent converters is expected, however, it is safe to assume that these WECs will be placed perpendicular to the dominant incoming wave propagation. Figure 4 provides a spatial optimal CF representation, the French channel has the "smallest" realised CF with $\approx$ 20%, as we move Northwards the Belgian coastlines have 25-35 %. Similarly, across the Dutch EEZ values of expected power production are $\geq$ 25%, increasing up to $\approx$ 45% found at Helgoland (German EEZ). Interestingly there is not one WEC that is optimal, the spatial distribution of devices support the idea that depending on depth a different WEC can be suitable (see Figure 5).

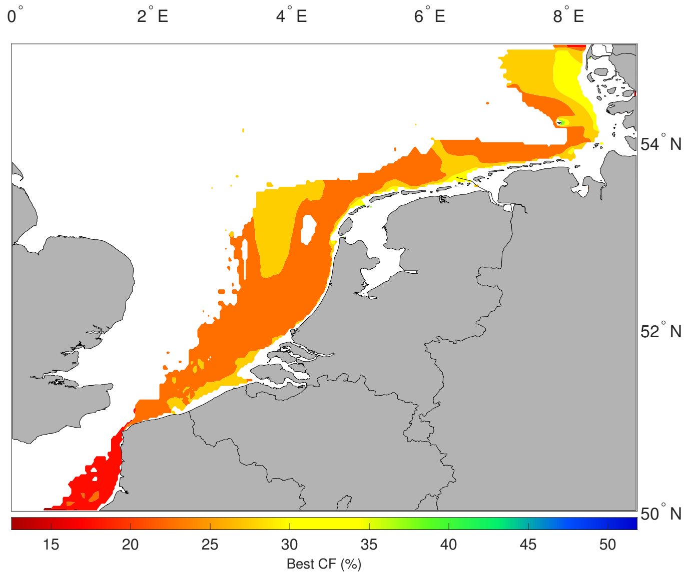

Fig. 4. Attained CF at the active locations, regardless of WEC, all options have been assessed simultaneously.

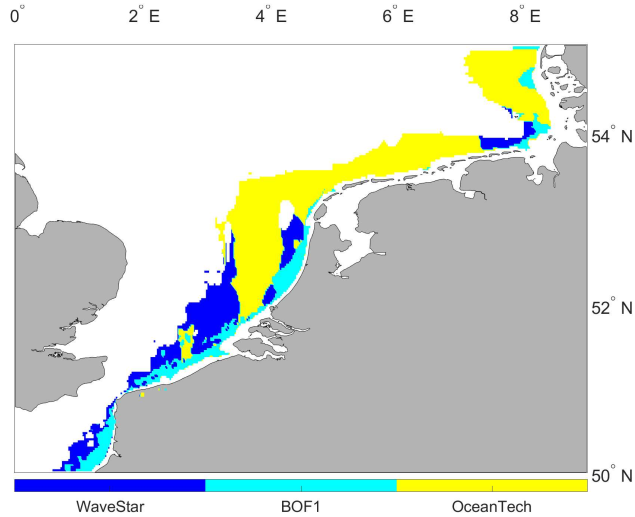

Fig. 5. Spatial distribution of "optimal" WECs for the domain.

In terms of LCoE the AEP can have detrimental effects into the viability of a wave farm. The discount rates chosen within this study can be considered conservative to pessimistic, in an effort to represent the high uncertainty in the market for wave energy. For the overall spatial mean CF of each device the LCoE have a wide range (see Figure 6 top panel), more specifically for Wavestar with discount rate 5% (red box plot) ranges from 150-500 €/MWh, similar though slightly lower is OceanTech for the same discount rate. For 5% discount rate and mean CFs BOF1 had the lowest values with 131-437 €/MWh. As the discount rates increase, indicating lower investor confidence, the LCoE tend to worsen. For the 10% discount lowest values are 159-182 €/MWh for all three WECs, with "worst" values 532-608 €/MWh.

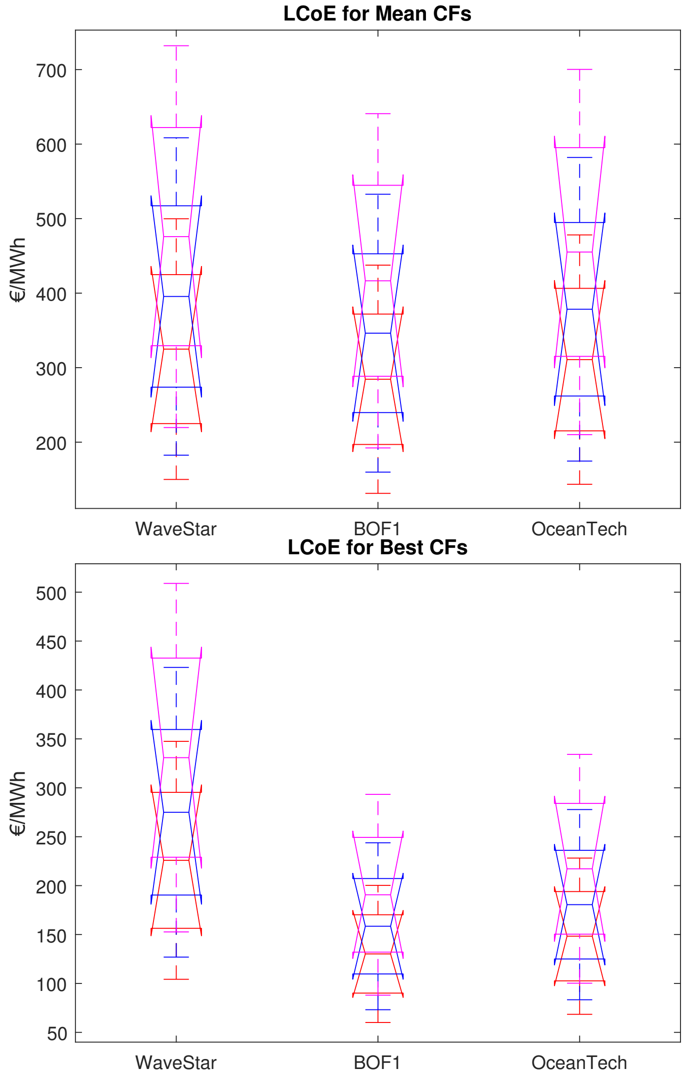

Fig. 6. LCoE distribution considering all CapEx ranges (1-5 million €) and the three discount rate scenarios with red 5%, blue: 10%, magenta 15%.

LCoE based on the optimal power production behaviour have considerable reductions in cost of energy (see Figure 6 bottom panel). BOF1 and OceanTech have similar values throughout the different discount scenarios. For a 5% discount rate LCoE are from 60-104 €/MWh, with higher ranges from 200-350 €/MWh. In the least favourable discount scenario LCoE are from 87-152 €/MWh for the lowest CapEx and for the highest from 293-500 €/MWh.

IV. Discussion

The economic feasibility of WEC can be considered as based on two set of parameters elastic and un-elastic. Elastic are the factors that can be altered by proper selection of location for installation, therefore AEP can be an elastic factor. Other elastic factors can be the lifetime of operation, and discount rates which have distinct effects in terms of LCoE and amortisation. However, arguably the highest impact amongst elastic factors is power production (AEP and/or CF). As an un-elastic factor CapEx and OpEx can be considered as main variables, with the latter (OpEx) able to be slightly reduced though its impacts will not be as much on LCoE.

WECs can be competitive in terms of LCoE with a combination of low CapEx (i.e. $\leq$ 3 million €/MW) and proper determination of WEC installed for a location, by utilising long term wave conditions as key indicators. The study focused at regions that can be considered as moderate resource levels, but even still the LCoE obtained are in the lower estimate ranges of literature. However, it has to be noted that the spread of minimum and maxima values are quite large (see Figure 6), regardless of discount rate.

The findings show that for milder resource region the design of a WEC should be smaller and with nominal capacity below of 1 MW, making them more adaptable to the higher frequency wave that occur. If properly placed the power production capabilities are equivalent of very good sites of onshore wind and marginally better that photovoltaic. Still LCoE uncertainty remains in the CapEx and discount (confidence) of the markets. However, with using interdisciplinary methods WEC farms are expected to comparable power production with mature renewable energies.

V. Conclusions

This study assessed the LCoE potential of wave energy for moderate resources. Unlike, past studies the power production capabilities were assessed over a long-term perspective, including Climatic differentiation, and using a high fidelity database that is also suitable for nearshore locations. This allowed us to reduce the uncertainty, assess multiple WECs, and identify which relationship between locations and WEC is more suitable.

The North Sea region shares the EEZs from several European countries, using a 38 year long-term wave database (NSWD) the energy content and metocean characteristics, allowed for robust estimates. In terms of wave energy flux upper latitude regions, from 51.5^o onwards, encompass the highest wave energy flux $\geq$ 12 kW/m, below 51^o the wave resource is reduced to 4-8 kW/m.

Several WECs with diverse principles of energy extraction and capacity were assessed, with smaller nominal capacity values ($\leq$ 1 MW) being more favourable for moderate conditions. Mean production potential, as expressed from CF varies, with the top three options having $\geq$ 20%. This in turn has implications on LCoE estimates, in fact for moderate resources, these first generation favourable WECs can obtain values as low as 60 €/MWh (with low CapEx and 5% discount rate). The LCoE based on mean CF behaviour and "regular" discount rates ranges from 131-500 €/MWh, with the most favourable WEC being from 131-437 €/MWh, with the latter price for a 5 million € Capex value. When the WEC is installed near its optimal, hence obtaining its highest power production the optimal device has an LCoE 60-200 €/MWh, for the predefined CapEx range (1-5 million €).

Wave energy has still a lot of obstacles to overcome, however, when using interdisciplinary methods and long-term suitable wave energy assessments, it is clear that power production reveals the untapped potential of a region. High resource locations, while they do carry almost double the wave energy flux, are also associated with higher survivability and loading issues, whilst not always translating the wave energy flux into a high power production capabilities. Moderate resource can assist in overcoming the uncertainties in reliable operation for WECs, and prove an alternative for evidence based funding of innovative technologies.

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