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RESEARCH ARTICLE

REVISED Mapping out the scenarios of ocean energy scale-up based on the development of offshore wind

[version 2; peer review: 1 approved, 4 approved with reservations]

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Abstract

Background

Our oceans remain one of the last untapped large sources of renewable energy. The predictability and reliability of marine energy technologies could contribute significantly to the global energy transition. By 2022, marine energy, and in particular wave and tidal energy have reached a pre-commercial phase in their development.

Methods

This study investigates the potential progression of the wave and tidal energy sector in the next three decades based on the offshore wind sector in the past three decades. Two different models were developed from the yearly capacity increase of offshore wind in Europe and applied to the wave and tidal energy sector.

Results

According to both models, the 40 GW 2050 target for marine energy set by the European Commission in 2020 could be reached if European coastal countries, including countries associated to the EU-27, adopt supportive policies for both technologies immediately. A sensitivity analysis shows further that a small delay right now will have tremendous negative impacts on fulfilling the EU goals and the contribution of marine energy to the energy transition.

Conclusions

Open Peer Review

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The ocean energy sector shows a strong growth potential and is capable of supporting the European and global climate targets substantially by 2050. Lessons learned from the offshore wind sector can help scope and support the growth of marine energy technologies.

Keywords
Wave, Tidal, Offshore wind, European targets, Policy recommendations, Offshore energy



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REVISED **Amendments from Version 1**

In the revised version, significantly more references are added to support the paper. Moreover, a flow chart is added at the beginning of the Method section that visualizes the key steps of the methodology of the paper. In the Methods section, an additional paragraph is added that lists all the forecast scenarios simulated by the models. Table 2 now includes the Learning Rates of both wave- and tidal power based on the approximation of the per-capacity LCoE. Lastly, the equations of the fit used to calculate the per-capacity LCoE of both wave- and tidal power are added.

Any further responses from the reviewers can be found at the end of the article

Introduction

Offshore renewable energy will contribute significantly to a reliable "Net Zero Emission" energy system by 2050[1]. The offshore energy transition is currently led by wind energy, but wave and tidal energy are also advancing fast. Those two are the most advanced technologies in the ocean energy sector which includes next to wave and tidal energy also ocean thermal energy conversion (OTEC) and salinity grandient energy. The predictability[2] and reliability of these technologies can help to improve grid forecasts and generally balance the grid to the demand[3]. Moreover, numerous studies have described synergies of a combined wave-wind park, including enhancing cost competitiveness of wave energy[4–6]. The global theoretical resource potential for tidal, wave and wind energy is 1,200[7], 18,500[8] to 29,500[7] and 36,000[9] TWh/year respectively. All three offshore renewable energy (ORE) sources together have a higher potential than the total world-wide electricity consumption in 2019[10].

Enabling this high potential is dependent on the techno-economic feasibility commonly measured via the Levelized Cost of Energy (LCoE) in comparison to the average day-ahead-electricity price. The average day-ahead electricity price is on a constant rise over the last decade and, fueled by the Ukrainian war, increased sevenfold between 2020 and 2022 to 235 €/MWh[11]. The LCOE of wind energy, tidal energy and wave energy was, in 2022, 81 EUR/MWh[12], 207 EUR/MWh[13] and 258 €/MWh[14], respectively. The targets established in the European SET plan aim for a LCoE of 100 EUR/MWh for tidal energy and 150 EUR/MWh for wave energy in 2030[15]. It is important to look at the LCoE in correlation with the planned capacity targets in Europe as both are highly interlinked and co-dependent. A higher installed capacity leads to cost reduction and performance improvements due to learning-rates and economy of scale. A lower LCoE in turn leads to more capacity installed due to a more competitive business-case. In 2020, the European Commission has set three targets regarding the cumulative capacity of ocean energy (100 MW in 2025, 1 GW in 2030 and 40 GW in 2050) and offshore wind energy commissioned (60 GW in 2030 and 300 GW in 2050)[16].

While by the beginning of 2022 33% of the time for the EU 2025 target has already passed, only 2% of the 100 MW capacity goal have been reached. However, around 112 MW of tidal and wave power are in the project pipeline in EU-27 waters (excluding affiliate countries) and could be deployed by 2025[17]. Next to these policy targets also research has been published by different European sector organisations and research centres. According to Ocean Energy Europe (OEE) which uses the Compound Annual Growth Rate (CAGR) methodology, between 1.5 GW (low growth scenario) and 2.88 GW (high growth scenario) of tidal and wave capacity could be deployed by 2030[18]. The Offshore Renewable Energy Catapult (OREC) found that LCoEs could be around 181 EUR/MWh for a total of 100 MW installed, 108 EUR/MWh at 1 GW installed and 94 EUR/MWh at 2 GW installed[19].

The development of the ocean energy sector is accelerating due to positive policy developments in the ranging from the innovation fund and Horizon Europe program in the EU[20], the Inflation Reduction Act with clear commitment to ORE in the US[21] and market pull frameworks like the contract for difference on tidal energy in the UK[22]. Japan[23], China[24] and the Republic of Korea[25] are already advancing their offshore wind industries and are also investigating how wave and tidal energy can complement their energy mix.

Assuming that the wave and tidal energy sectors are on the brink of commercial feasibility, it is important to establish the sector's potential contribution to the energy system in the next decades The most commonly used energy system models (DNV[26], IEA[27], etc.) are not yet including wave and tidal energy. Only a few, including the [R]Evolution scenario of Greenpeace which calculate the ocean energy capacity in OECD Europe by 2050 to be 53 GW[28] and the IRENA 1.5 degrees model, which aims for 351 GW worldwide by 2050[29]. To provide sufficient data to have more energy system reports including ocean energy in a reliable way, the capacity growth of the more mature bottom-fixed offshore wind sector can be applied to the expected growth of wave and tidal energy. These ORE sectors share many comparable aspects regarding installation environment, required supply chain, operation and maintenance procedures and electrical infrastructure. The offshore wind sector has been growing exponentially in Europe since the 1990s. In 2021, almost 26 GW of offshore wind are commissioned and 100 GW more could be deployed by 2030[30].

In this study, the three decades of offshore wind deployment from 1990 to 2020 are analysed to draw various forecast scenarios on the operating capacities and LCoE reduction for wave and tidal energy until 2050 in Europe. Based on the forecast of the development of the tidal and wave energy sectors the feasibility of meeting the European ocean energy targets regarding the capacity deployed and the LCoE is evaluated. The behaviour of the offshore wind market is further linked with policy support mechanisms showing the necessity of supportive policies for ocean energy technologies in European coastal countries.

Methods

Figure 1 presents a flowchart summarizing the methodological steps used to develop the cumulative growth curve and doubling time models for wave and tidal energy. It outlines the process from data acquisition to model development, detailing the determination of the reference year for offshore wind and the derivation of growth parameters based on deployment data from 1991–2021. These growth curves were adapted for tidal and wave energy by identifying their respective pre-commercial phases and establishing starting capacities. The flowchart provides a visual guide to these steps, which are elaborated upon in the following sections.

Data acquisition

The wave and tidal energy sector development trajectories in this paper were based on the offshore wind growth in the past three decades. A database listing all the offshore wind farms in the pipeline, under-construction, commissioned and decommissioned within Europe was used (published along with this article). Only bottom-fixed offshore wind farms were considered as the offshore floating wind sector in 2022 was still at the early stage of commercial deployment. The first offshore wind array commissioned in Europe was named Vindeby and was installed off the coast of Denmark in 1991. Based on this first commercial array installation, the reference year for the offshore wind sector was consequently set to 1991. Both commissioned and decommissioned offshore wind farms were considered for the study.

In total, the data from 119 offshore wind farms was used to compute the results from eight different countries (BE, DE, DK, FI, IE, NL, SE, UK) from 1991 until 2021. An exponential growth curve and doubling time model was deducted from this dataset and applied to the wave and tidal energy sector. For both technology types the starting year and value equaling the offshore wind sector in 1991 were carefully assessed.

Starting values and years for wave and tidal

Between 2010 and 2021, 30.2 MW of tidal stream energy converters have been installed in Europe since 2010, of which 11.5 MW were in the water in 2021 and 12.7 MW of wave energy converters have been installed, of which 1.4 MW were in the water in 2021[31]. A database of all those deployments was used to define the starting year and value.

First, the status of the technology developers in the database was checked and companies who have since disappeared or are hibernating for a prolonged time-period were filtered out. Second, the starting dates of entering the pre-commercial phase for both the wave and tidal sector were established based on publicly available data. The basic characteristics of the pre-commercial phase are: existence of Power Purchase Agreements (PPAs), first array installations, increased investor interest and policy support. Third, the starting year was matched with the cumulative capacity of still operating technology developers in that year resulting in the starting value.

For the tidal sector, 2016 was established as the year where the sector entered a pre-commercial phase. The dominating contribution came from Nova Innovation, Tocardo and the SIMEC Atlantis project (including turbines from Andritz Hydro). All three technology developers started to install the first turbines of larger-scale projects at that time. Together they had 3.05 MW installed which was considered the starting value for tidal energy in 2016. Additional active European technology developers who were not considered because they were in 2016 still more in a demonstration phase or deployed outside of Europe include Schottel Hydro, SME, Sabella, and ORPC.

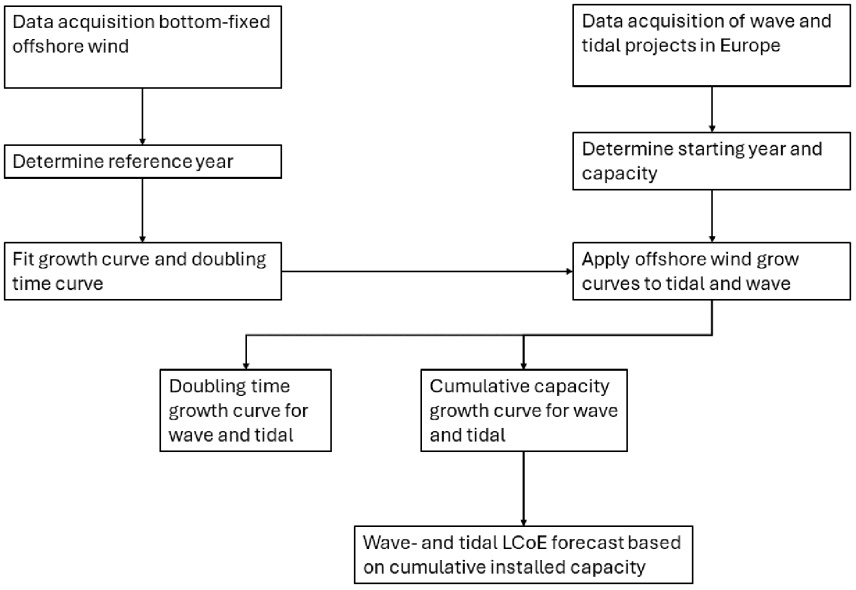


Figure 1. Figure 1 depicts a flowchart summarizing the key steps that were used to build the model presented in this paper. Each step will be further elaborated upon in this section.

For the wave sector, 2020 was established as the year where the sector entered a pre-commercial phase. In 2020 the constructions of the first MW scale systems started. Some prominent examples are the Corpower Ocean Wave Energy Converters array in Portugal, the Wello system in Spain and the full-scale demonstration of the Irish developer Ocean Energy in Hawaii. Others like EcoWavePower, Seabased and AW Energy demonstrated large-scale devices or arrays with PPAs and showed a large project pipeline. Combined with several additional offshore tested technology developers a critical mass of wave energy companies has been reached. Altogether this means that the entrance into a pre-commercial stage started in 2020. Altogether those companies had a cumulative capacity of 6.11 MW in 2020, which was chosen as the wave model starting value (Table 1).

An important difference between offshore wind and some bottom-fixed tidal systems on the one side and wave energy devices on the other side is the ease by which the latter can be deployed and towed back to shore for maintenance or improvements. Therefore, the cumulative capacity of companies still actively operating in the sector was used as the starting value for the wave energy sector, while only pre-commercial deployments were used for the tidal energy sector.

Table 1. Tidal and wave developers taken into consideration to choose the starting values.

Tidal developers	Wave developers
Tocardo (NL)	40South Energy (IT)
Nova Innovation (UK)	AMOG (AU)
SIMEC Atlantis Energy (UK)	AW-Energy (FI)
	CorPower Ocean (SE)
	Crestwing (DK)
	Eco Wave Power (SE)
	Floating Power Plant (DK)
	Fred Olsen Ltd (UK)
	GEPS Techno (FR)
	Hace (FR)
	Havkraft AS (NO)
	Marine Power Systems (UK)
	Ocean Energy (IE)
	Resen Energy (DK)
	Seabased (IE)
	SINN Power (DE)
	Voith Hydro (DE)
	Wave for Energy (IT)
	Wavenergy (IT)
	Wavepiston (DK)
	Waves4Power (SW)
	Wedge (SP)
	Wello Oy (FI)

Growth curve model

The first model - named "Growth curve model" - was developed based on an exponential fitting of the offshore wind cumulative capacity over the years. Firstly, the data was collected and only offshore wind farms commissioned and decommissioned between 1991 and 2021 in Europe with bottom-fixed foundations were taken into consideration. Secondly, the offshore wind turbine capacities were summed for each year and the decommissioned offshore wind turbines were subtracted whenever they have been decommissioned. Thirdly, a cumulative sum over the years was computed.

In order to apply the growth curve from the offshore wind sector to the marine energy sector curve fitting was applied. The curve fitting was performed to achieve the highest correlation between the function and the real curve, determined by the coefficient of determination R^2 values. The most appropriate function identified was an exponential split into three ten-year intervals (coefficients of determination between 0.915 and 0.993): (1) the "lag phase" from 1991 until 2001, (2) the "kick-off phase" from 2001 until 2011 and (3) the "growth phase" from 2011 until 2021 (and still going). If no intervals were considered an even higher average coefficient of determination was achieved (0.988). This, however, showed weak correlation with the datapoints in early years with low cumulative capacity. While the small values only led to small total derivation, the difference to what was really deployed was a factor 10 in the first 10 year interval (namely the "lag phase"). While this divergence did not weigh strongly for the overall correlation calculation it had a too strong influence on the prediction of the early growth of the sector.

The exponential coefficients of the growth curve were obtained by using the *curve_fit* Python function (last access: July 2024), applied to the following equation:

$$P = a * e^{b*t_y} + P_{y,0} - a * e^{b*t_{y,0}} \quad (1)$$

where a and b are the two coefficients computed by the *curve_fit* function, P the cumulative capacity in MW, t_y the number of years since the year of reference, $P_{y,0}$ and $t_{y,0}$ the first values of the interval.

The coefficients of the three exponential functions were then applied to the wave and tidal energy sector. Depending on the starting point, a 30-year period was not always sufficient to reach 2050. In that case, the remaining years were extrapolated with the exponential coefficients of the last interval.

The coefficient of determination R^2 was computed using the following equation:

$$R^2 = 1 - \frac{\sum_i (y_{dataset,i} - y_{fitting,i})^2}{\sum_i (y_{dataset,i} - \overline{y}_{dataset})^2} \quad (2)$$

where $y_{dataset,i}$ is the offshore wind cumulative capacity (from the dataset), $\overline{y}_{dataset}$ is the mean of the offshore wind cumulative capacities for each interval and $y_{fitting,i}$ is the offshore wind cumulative capacity given by the model. The closer R^2 approaches 1 the better the correlation between the dataset and the applied function. R^2 values above 0.9 are acceptable.

Doubling time model

The second model was based on the number of doubling events during the 30-year period. A doubling event is defined as the doubling of the installed capacity of the renewable energy technology globally or in a certain area. The doubling event computation is frequently used when analysing the behaviour of a sector. In the renewable energy sector, it is typically used for learning rates but it can also be useful for other techno-economic calculations.

The doubling time method is equivalent to the CAGR method which is used in other studies forecasting the growth of the marine energy sector[18].

Not only the number of doublings were computed but also the length of time between two doublings. These values gave the opportunity to have a more relatable idea of how a sector is growing. It was computed using the following equation:

$$T_d = (t_2 - t_1) * \frac{ln2}{ln\frac{P_2}{P_1}} \quad (3)$$

where, T_d is the length of time between two doublings, t_1 the first year of the interval, t_2 the last year of the interval, P_1 the cumulative capacity for the first year of the interval in MW and P_2 the cumulative capacity for the last year of the interval in MW.

The 30-year period was again split into six five-year intervals to have a high coefficient of determination (R^2 = 0.995). A five-year interval was chosen and the growth rate inside the interval was assumed constant. The values used to compute the number of doublings were the same as for the growth curve scenario, i.e. the cumulative capacity over the years of the European bottom-fixed offshore wind farms, minus the decommissioned offshore wind turbines.

The number of doublings were computed using the following equation:

$$N = \frac{ln\frac{P_2}{P_1}}{ln2} \quad (4)$$

where N is the number of doublings, P_1 the cumulative capacity for the first year of the interval in MW, P_2 the cumulative capacity for the last year of the interval in MW.

The number of doublings from the offshore wind sector was applied to the marine energy sector using the following equation:

$$P = P_0 * 2^N \quad (5)$$

where P is the new value of the cumulative capacity for the last year of the interval and P_0 the cumulative capacity value for the first year of the interval.

Between the two boundaries of the 5-year interval, the growth rate was assumed constant and the curve followed an exponential growth following the equation displayed below:

$$P(t) = P_0 * 2^{\frac{t}{T_D}} = P_0 * e^{r*t} \quad (6)$$

where $P(t)$ is the cumulative capacity after a timeinterval t, P_0 is the cumulative capacity for the first year of the interval, T_d the length of time between two doublings (known thanks to the offshore wind sector computing), r the constant growth rate and t the length of time in years.

Similar to the growth curve model and depending on the starting point, a 30-year period was not always enough to reach 2050. In that case, the remaining years were extrapolated with the average of the number of doublings for the last three intervals known.

The real offshore wind cumulative capacity and the trendlines from both models are displayed in Figure 2. The coefficients of the trendlines and the number of doublings displayed within the Figure were then used to compute the forecasts for the marine energy sector.

The coefficients of determination R^2 for the exponential fittings of the offshore wind cumulative capacity in the growth curve model and the doubling time model were all above 0.9 (and even higher than 0.95 for two intervals of the growth curve fitting and the doubling time fitting) which means that both models were close to the original dataset.

Levelized Cost of Energy forecast

The growth- and doubling time models for wave- and tidal energy are combined with an projected LCoE forecast of Ocean Energy Europe (OEE)[18] based on an Ocean Renewable Energy (ORE) Catapult analysis[19]. This forecast predicts the reduction of LCoE for wave- and tidal energy as the installed capacity increases (Table 2). The tidal stream forecast follows the methodology described for the offshore wind sector[19], where the starting LCoE was determined to be 361 EUR/MWh for the 10 MW installed at the time[18]. The wave forecast employed the same methodology[19], but uses the tidal stream's learning rates, cost of capital and project development costs as well as a higher starting value as initial wave deployments were more expensive than tidal stream

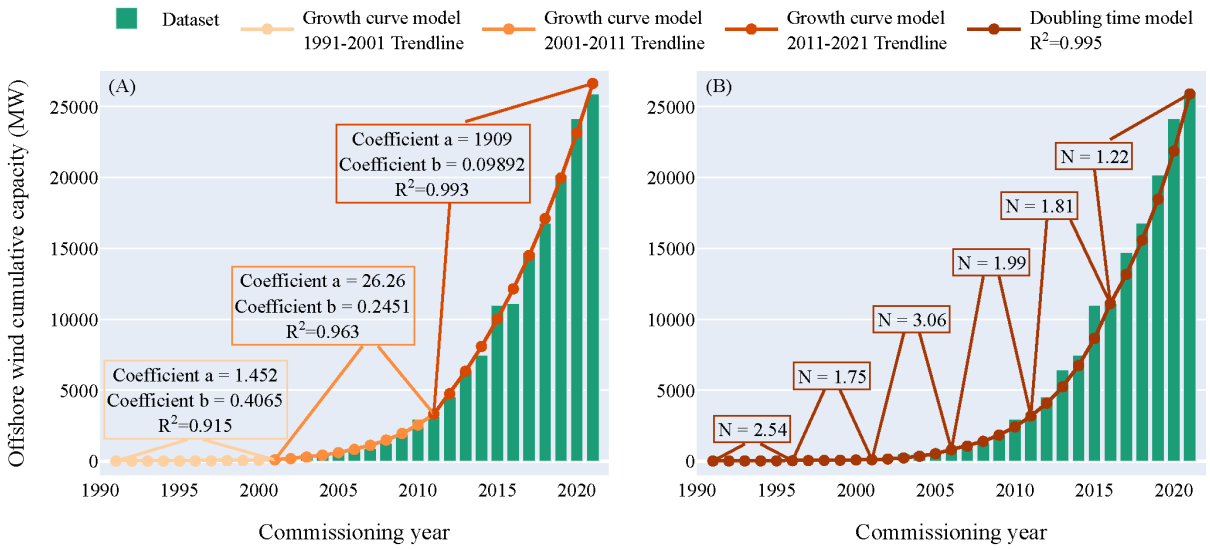


Figure 2. Offshore wind cumulative capacity over the commissioning years. (**A**) Growth curve model. Coefficients a and b are the two coefficients computed by the curve_fit function used to draw the exponential fitting curve. The fitting curve is split into three ten-year intervals: the "lag phase", the "kick-off phase" and the "growth phase". The coefficient of determination is higher than 0.9 for the three intervals. - (**B**) Doubling time model. N is the number of doublings. The whole period is split into six five-year intervals in order to follow the original dataset closely. The global value of the coefficient of determination is higher than 0.99 which indicates that the model is close to the original dataset.

Table 2. LCoE forecast. Columns 2 & 3 are adapted from 18, columns 4 & 5 are the calculated Learning Rates (LR).

Cumulative capacity (MW)	Tidal LCoE (€/MWh)	Wave LCoE (€/MWh)	Tidal LR (%)	Wave LR (%)
1	616	702	0.0	0.0
5	489	546	9.5	10.5
10	361	387	26.2	28.7
20	267	269	26.0	30.5
50	214	207	15.4	18.0
100	181	168	15.4	18.8
200	154	136	14.9	19.0
500	126	110	14.1	14.8
1,000	108	92	14.3	16.4
2,000	94	81	13.0	12.0

deployments at the time[18]. A comprehensive description of the methodology adopted for the LCoE forecast is given in 18. A learning rate curve fit has been applied to Table 2, using the curve fit function of Python's Scipy package (last access: July 2024) to create a set of equations that provides an interpolated approximation of the per-capacity LCoE reduction for tidal (Equation 7) and wave (Equation 8).

$$LCoE_{tidal} = 736.37 \cdot x^{-0.30} \quad (7)$$

$$LCoE_{wave} = 641.58 \cdot x^{-0.26} \quad (8)$$

Where, LCoE is the predicted LCoE [EUR/MWh] and x is the installed capacity of either wave- or tidal energy.

Equation 7 and Equation 8 have been applied to the installed capacity output by the growth- and doubling time models to obtain an approximation of the per-capacity LCoE.

Scenarios

The main scenario presents the output of the growth curve model and the doubling time model based on the fits described above and using the identified starting years. Three scenarios with different starting years (2015, 2020, and 2025) and three scenarios with different starting cumulative capacities (1 MW, 5 MW, and 10 MW) are considered to determine the sensitivity of both models to varying parameters. Moreover, a best-case scenario is presented. Here, the "lag phase" fit observed for offshore wind is assumed to be avoided for the growth of ocean energy due to uncompromising policy support.

Results and analysis

In order to understand the growth of the marine energy sector in the next three decades the exponential growth and doubling time function were established for offshore wind (Figure 2) and applied to the ocean energy sector. In 2016 and 2020 the starting capacity for tidal energy was estimated to 3.05 MW and the one of wave energy to 6.11 MW, respectively. Combining the starting capacities and years of wave and tidal with the exponential growth curve of offshore wind resulted in two growth curves per technology (Figure 3, Figure 4).

The tidal energy sector entered its pre-commercial phase in 2016. Therefore, the amount of capacity that could be

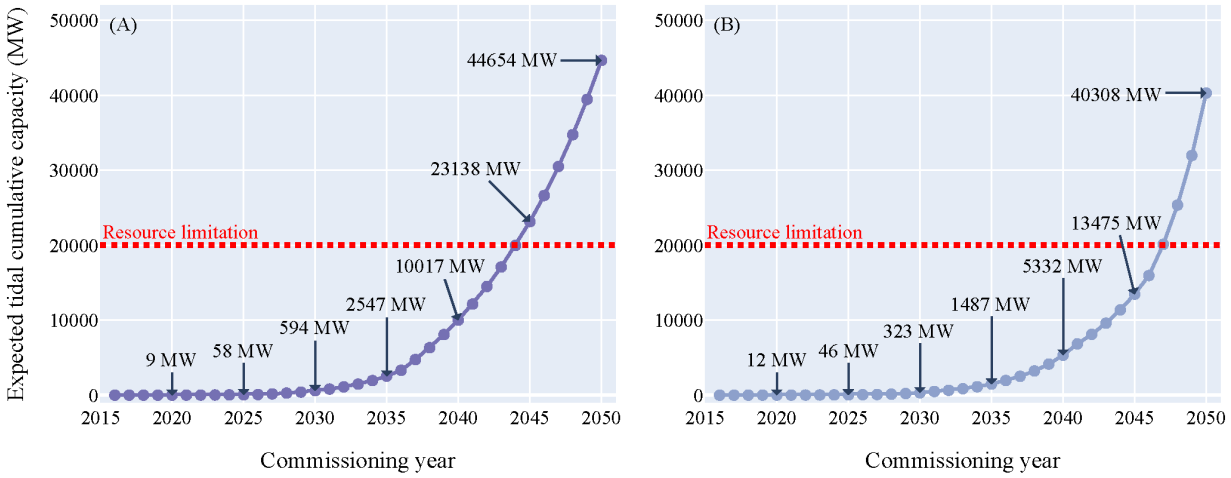


Figure 3. Expected tidal cumulative capacity over the commissioning years. (**A**) Growth curve model - (**B**) Doubling time model. Both models returned values with the same order of magnitude: between 46 and 58 MW could be deployed in 2025, between 323 and 594 MW in 2030 and between 40.3 and 44.7 GW in 2050. The red line displayed on the figure represents the tidal energy technical potential limitation in Europe which is around 20 GW. This limitation will be reached between 2044 and 2047 according to the models.

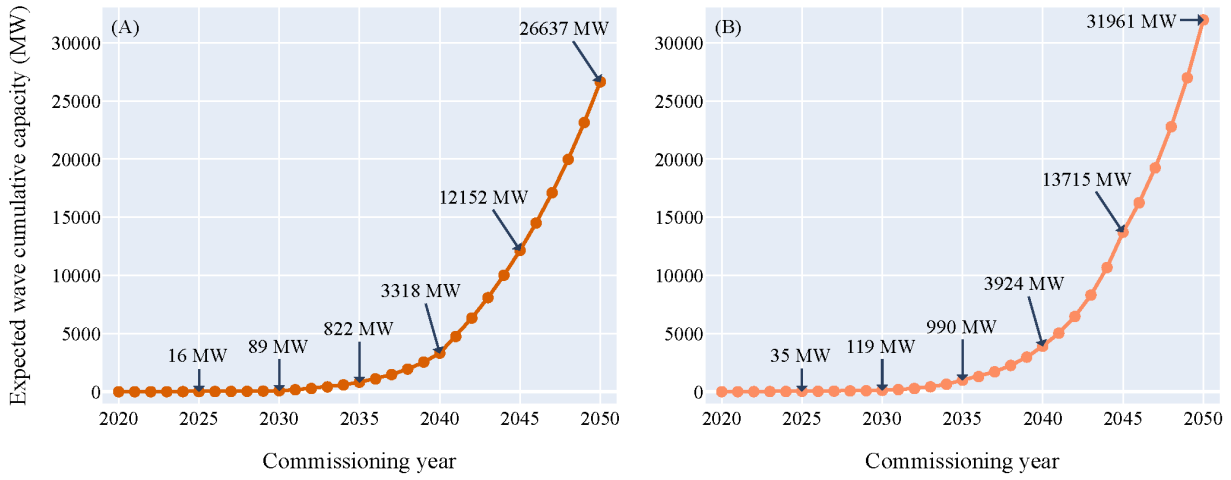


Figure 4. Expected wave cumulative capacity over the commissioning years. (**A**) Growth curve model - (**B**) Doubling time model. According to both models, between 16 and 35 MW of wave power could hit the water by 2025, between 89 and 119 MW by 2030 and between 26 and 32 GW by 2050. As the wave energy technical potential in Europe is not expected to be reached by 2050, the sector will likely keep growing significantly after 2050. The wave energy resource potential limitation (around 100 GW) is outside the graph boundaries and will not be met by 2050 according to both models.

commissioned in the upcoming years according to the models is higher than for wave energy. The analysis showed that around 50 MW in 2025 (half of the European target) and between 320 and 600 MW in 2030 would be achievable. Between 2040 and 2044, 10 GW could be deployed and in 2050 between 40.3 and 44.7 GW of tidal power could theoretically be reached.

The wave energy sector reached its pre-commercial phase about four years after the tidal energy sector in 2020. Therefore, the deployed capacities in the upcoming years are lower than for tidal. In 2025, between 16 and 35 MW could be commissioned and between 89 and 119 MW in 2030. According to both models, 10 GW could be in the water in 2044. In 2050, between 26 and 32 GW of wave power could be deployed in Europe.

Assessment of the resource potential

The results of the model were compared to the energy resource potentials to verify if the results are realistic. Depending on the technologies used to produce electricity, the efficiency varies. Therefore, there is a difference between the theoretical

resource potential, which covers the total extractable amount of energy, and the technical resource potential, which includes limitations of current technologies.

For tidal energy, the technical resource potential limitation taken into consideration for this study is 20 GW[19,32]. The 20 GW limitation for tidal cumulative capacity could be reached in 2044 for the growth curve scenario and in 2047 for the doubling time scenario.

For wave energy, the technical energy potential in Europe is between 95 GW (Schlütter *et al.*[33]), 286 GW[34] and as high as 50 TW[35]. According to both models, this limitation is not expected to be reached by 2050. Therefore, the expected cumulative capacity for tidal and wave energy combined could reach between 46.6 and 52 GW in 2050.

European targets

According to the models, wave and tidal capacity will be crucial to meet the 100 MW target by 2025 set by the European Union. The remaining capacity (less than 30 MW) could be partly filled with salinity gradient power plants, OTEC power plants or floating solar modules.

In the same way, the 2030 target of 1 GW will not be reached. Depending on the model considered, between 44 % and 68 % of the target could be filled with wave and tidal energy (Figure 5). The remaining capacities would need to come from other marine energy technologies.

According to both models, the 40 GW target by 2050 is expected to be overtaken by 6 to 12 GW. Furthermore, adding floating solar, salinity gradient and OTEC capacities, the 2050 target can be even further overtaken. Important to note is that the UK was considered to contribute to the European targets.

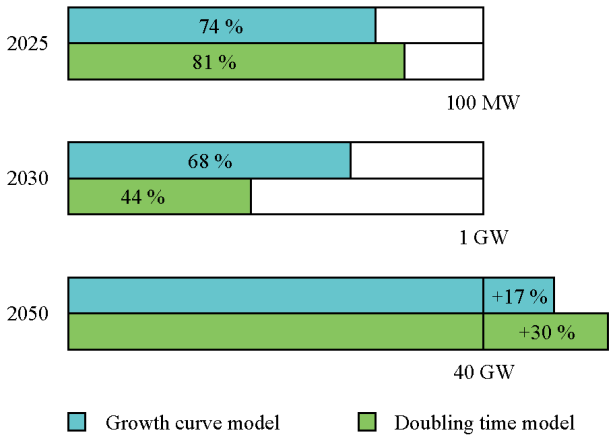


Figure 5. Completion percentage of the European targets. According to both models, the 2025 and 2030 targets will not be reached. Yet, the 2050 target could be overtaken. In order to get closer to the 2025 and 2030 targets, intensive support from European coastal countries are needed.

Levelized Cost of Energy forecast

Following the methodology given above, the expected LCoE over the commissioning years for each model and each technology are computed (Figure 6).

It is generally accepted that a five-year delay between tidal LCoE and wave LCoE will occur[15]. Yet, according to the models, the delay should be around five years during the first commercial deployment phase and then could shorten gradually until 2035 where the LCoE for both technologies will likely be equivalent.

The European Commission set targets for wave and tidal energy LCoE in the SET Plan[15]: 100 EUR/MWh for tidal energy and 150 EUR/MWh for wave energy by 2030. The targets for 2030 will be slightly delayed. According to both models, the 100 EUR/MWh target for tidal energy could be reached between 2033 and 2035 and the 150 EUR/MWh target for wave energy could be met in 2031. The forecasts given by OEE and in this study show consistency with the newest developments in tidal energy. In particular the award of 41 MW of tidal energy in the UK at a strike price of 208 EUR/MWH aligns well with the predicted 214 EUR/MWh for 50 MW[36].

Sensitivity analysis of both models

A sensitivity analysis was conducted for both models to understand how the models react when the starting year and the starting value vary (Figure 7). Three different starting values (1 MW, 5 MW and 10 MW) and three different starting years (2015, 2020, 2025) were computed.

The variation of the starting year moves the curve to the left or to the right for both models. Therefore, as the growth is exponential, the expected capacity in 2050 changes drastically. For the growth curve model, if the starting year happens five years before, then the operating capacity in 2050 would be multiplied by 2.2. On the contrary, if the starting year happens five years later, then the operating capacity would almost be reduced by half. Regarding the doubling time model, the variation is even higher. A decrease of five years in the starting year leads to a 3.2 times higher capacity and an increase of five years leads to a 2.3 times lower capacity. The variation of the starting value does not have a significant effect for the growth curve model as it is only moving the curve up or down by the difference of the starting capacity. Therefore, a 5 MW variation of the starting value leads to a 5 MW difference in 2050, which is insignificant compared to the GW scale at this point. For the doubling time model, the variation of the starting value has a significant effect. If the starting capacity is doubled, then in 2050 the expected capacity will be doubled too. The starting year and the starting value are intrinsically linked but this analysis

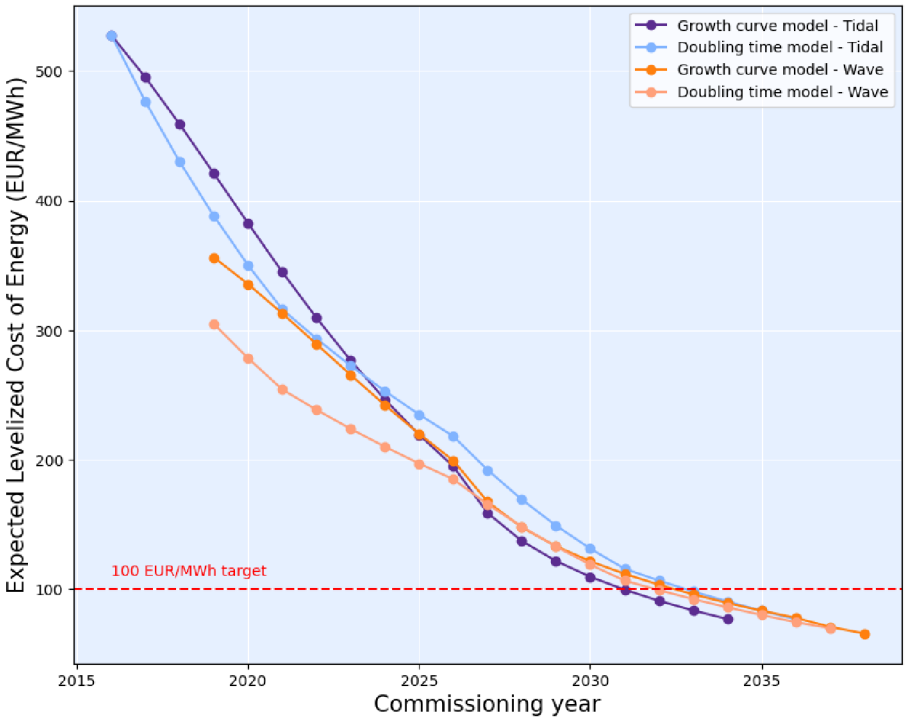


Figure 6. Expected LCoE over the commissioning years (the OEE dataset give the LCoE between 1 MW and 2000 MW of cumulative capacity). The 100 EUR/MWh target set by the European Commission could be reached, for both technologies, around 2035. The wave LCoE is higher than the tidal LCoE for the first capacities deployed but as more capacities hit the water, the LCoE for both technologies comes closer together.

clearly highlights that a few years delay in the start of the first commercial deployments will significantly influence the operating capacities in 2050.

Offshore wind support schemes

In 2022, five countries lead the European offshore wind market: Belgium, Denmark, Germany, the Netherlands and the United Kingdom with various offshore wind support mechanisms (Figure 8). The average length of time between the awarding of an offshore wind farm and its commissioning is around five years[37]. Therefore, the effect on capacity installed of new support schemes only materializes five years after. To reach the European targets for marine energy but also for offshore wind, shorter commissioning times are required. This result is consistent with the 5-year delay between the establishment of a new support scheme and the commissioning of offshore wind farms in various European countries (Figure 8). Therefore the marine energy sector does not only need subsidies but also needs to reduce the time needed for commissioning of new offshore farms. The latter can be accomplished by an already established offshore supply chain, usage of satellite data to shorten offshore measurement campaigns, a detailed generally agreed on marine spatial plan and parallel permitting procedures instead of cascading ones taking all offshore renewables into consideration.

Similar to offshore wind, these subsidies will allow wave and tidal energy to mature and learn until they become profitable without direct subsidies from the government (e.g. Dutch offshore wind sector 2021). One way of structuring those different support schemes and subsidies in a transparent way ensuring the timely execution of projects, are offshore renewable tenders. Those tenders can specify what exactly the government supplies, what the boundaries are and what the goal of the tender is. A bidding system on those tenders increases competitiveness and value for money. An important indirect subsidy often interlinked with a tender structure is the provision of the offshore grid. This comes with the positive side-effect that the offshore grid will not only be optimized on the project developers profit, but also on energy security and overall system costs.

Best case scenario

If an uncompromising policy support is set quickly to assist the tidal and wave energy sector growth, a very fast development of new or hibernating projects can be expected. It could

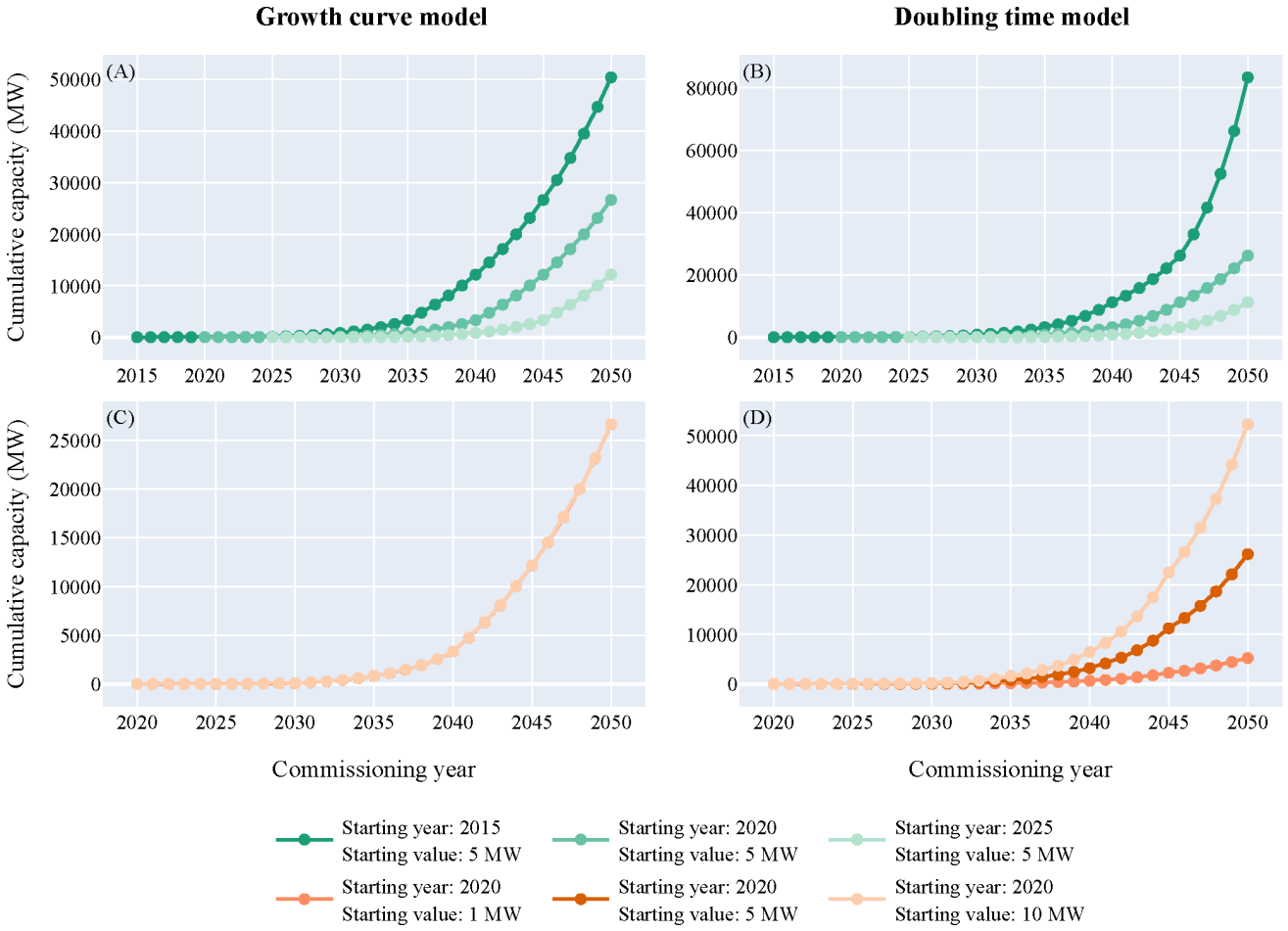


Figure 7. Sensitivity analysis of both models. (**A**) Growth curve model, varying parameter=starting year - (**B**) Doubling time model, varying parameter=starting year - (**C**) Growth curve model, varying parameter=starting value - (**D**) Doubling time model, varying parameter=starting value.

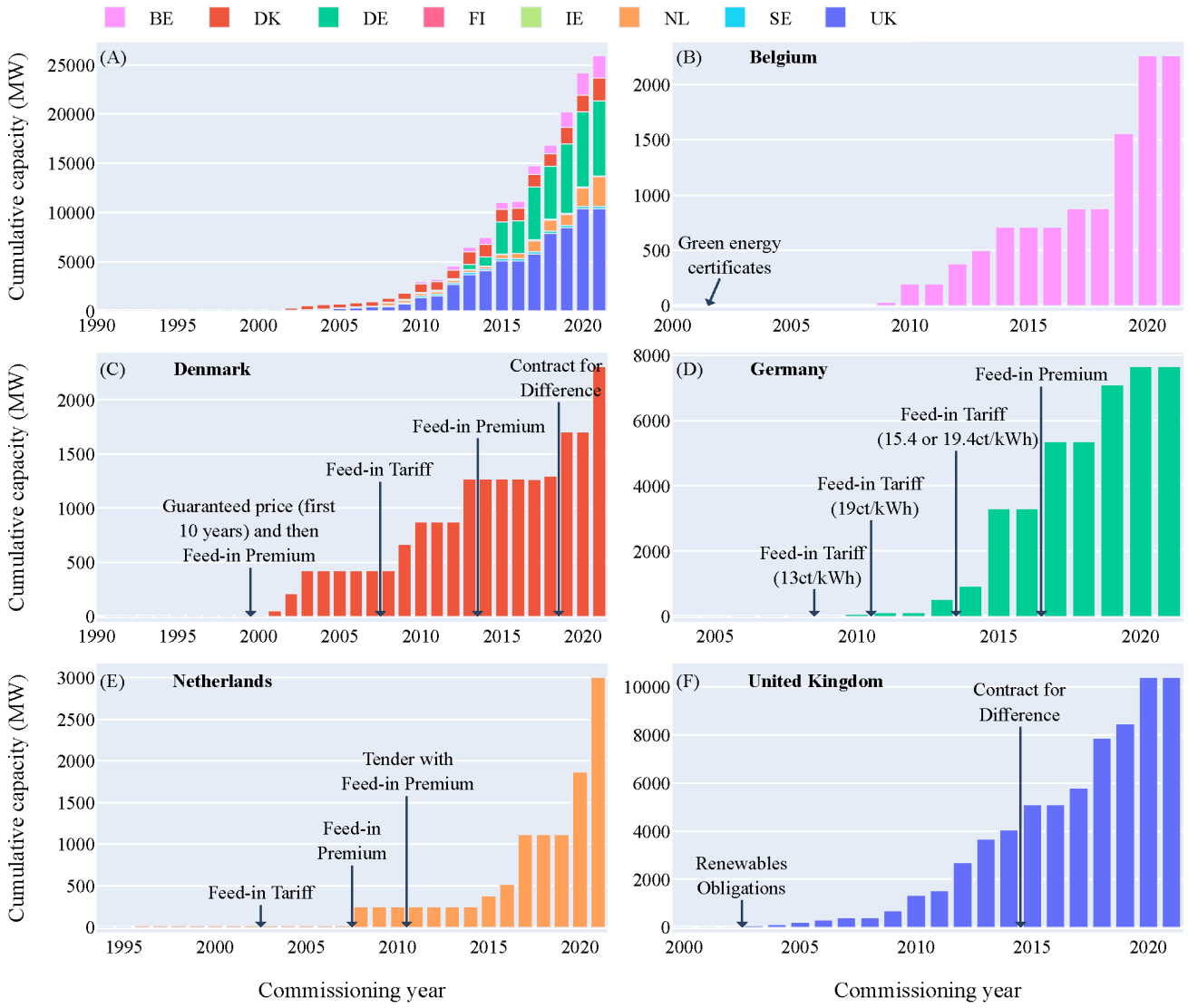
also lead to a consolidation of technologies with a standardization of components used in wave and tidal devices. This standardization will further reduce the costs as supply chains become more competitive and reliable. Moreover, the tidal and wave sectors could benefit from the existing offshore supply chain developed for the offshore wind sector.

By introducing support schemes to support the sector immediately the "lag phase" that occurred for the offshore wind sector in the 1990s is avoided and the 2025 and 2030 European targets can be met as well.

The second phase of the offshore wind development started around 2001 with the introduction of support schemes. When computing the growth curve model using 2001 as the new starting year for offshore wind and 2023 as the starting year for both the tidal energy sector and the wave energy sector (see Appendix, Figure 10), the 2025 and 2030 European targets regarding the operating capacity could be greatly overtaken (Figure 9). The starting values taken into consideration are 26.58 MW for the tidal sector and 9.57 MW for the wave sector. These values are obtained by computing the growth curve model using the initial starting points and considering the expected cumulative capacity in 2023.

Discussion and conclusion

A huge amount of untapped energy is located in our oceans and seas. Ocean energy technologies like wave and tidal are needed to tap this last big reservoir of renewable energy and are needed to meet a global "Net Zero Emission" energy system. Different pathways can reach this target, where a highly renewable energy system is likely to be the most efficient, also cost-wise[38]. Although ocean energy has been considered in small-scale 100% renewable energy systems on islands[39], for global 100% renewable energy systems, wave, and tidal energy are rarely included as part of the renewable energy mixture[38]. Europe is leading the ocean energy sector but the US and China are also catching up. Only by a fast



Support scheme	Description
Quota	Named "Green certificates" in Belgium and "Renewables Obligation" in the United Kingdom. A certificate is issued for each MWh of electricity produced from offshore wind. The power plant operators can sell them on a specific market and get additional revenues on top of the electricity market revenues.
Feed-in Tariff	A fixed sale price is guaranteed for each MWh of electricity produced.
Feed-in Premium	A fixed sale price is guaranteed for each MWh of electricity produced on top of the revenue from the electricity market.
Contract for Difference (CfD)	The difference between the electricity market price and a pre-defined price has to be paid by one of the two parties (namely the generator and the buyer). There are two different types of CfD: two-sided or one-sided. For the two-sided CfD, if the trade price is higher than the predefined price, the seller will pay the buyer the difference and if the trade price is lower than the predefined price, the buyer will pay the difference to the seller. In contrary, for the one-sided CfD, even if the trade price is higher than the predefined price, the buyer will have to pay the difference to the seller.

Figure 8. (**A**) Offshore wind cumulative capacity over the years for each European country - (**B**) Offshore wind support schemes in Belgium - (**C**) Offshore wind support schemes in Denmark - (**D**) Offshore wind support schemes in Germany - (**E**) Offshore wind support schemes in the Netherlands - (**F**) Offshore wind support schemes in the United Kingdom. The first figure highlights the five European leading countries for offshore wind in terms of capacity deployed. Four different support schemes were used during the past 20 years: Feed-in Tariff, Feed-in Premium, Contract for Difference and Quota.

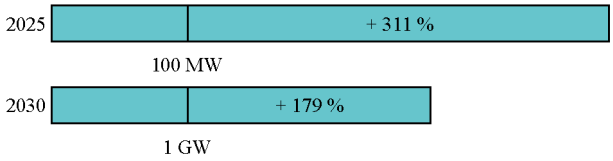


Figure 9. Completion percentage of the European targets in the best case scenario using the growth curve model. The European targets could be greatly overtaken if actions are taken now.

implementation of strong support policies to further develop it, Europe will stay on top generating unique export opportunities. Doing so and considering all limitations both the wave and tidal sector will likely grow similarly to offshore wind. In the last three decades, more than 25 GW of offshore wind was commissioned in European waters. This study, based on the development of the offshore wind sector, forecasts around 50 GW of wave and tidal operating capacity in Europe by 2050. According to the models developed for this study, the full technical potential of 20 GW of tidal energy could be deployed between 2044 and 2047. Following the offshore wind growth, intermediate values between 46 and 58 MW in 2025 and between 323 and 594 MW in 2030 are realistically achievable. Regarding the wave operating capacity, between 26 and 32 GW could be deployed by 2050. As the resource potential in Europe for wave energy is far higher than that, further growth after 2050 is likely. Moreover, between 16 and 35 MW of wave energy could be deployed by 2025 and between 89 and 119 MW by 2030. According to the models and based on the limited policy commitments of European coastal countries to this date, the European targets set for 2025 and 2030 (respectively 100 MW and 1 GW of marine energy) will not be met. In total, between 74 and 81 MW of wave and tidal energy could be deployed by 2025 and between 442 and 683 by 2030. Other ocean energy technologies such as OTEC and salinity gradient will unlikely be enough to fill the gap in those years. In 2050, taking into consideration the tidal resource limitation, between 46.6 GW and 52 GW could be deployed, greatly overtaking the European target of 40 GW. Based on the results from both models and the LCoE forecasts from OEE, the 100 EUR/MWh LCoE target for tidal energy could be met in 2033, and the one for wave energy in 2035. This cost reduction makes the sector cost-competitive to other energy sources. However, considering the international developments in 2022 and the tremendously increased cost of electricity one could argue that those technologies are already price competitive if being installed in arrays. Thus, both tidal and wave can be considered, in terms of resource availability and economic competitiveness, as part of a future high renewable energy system and could provide a step forward towards a global "Net Zero Emission" energy system, as well as diversify the renewable energy mixture, enhancing energy security and grid reliability[3,40,41].

The main assumption of this study is that the tidal and wave energy sectors will behave the same way as the offshore wind sector did in the past. Wave and tidal could develop faster than offshore wind, as they can build upon challenges already overcome by offshore wind, such as grid connection, operation & maintenance, etc. However, if we want the marine energy sector to grow the same way, or even more faster than the offshore wind sector, we need to be sure that the marine energy sector benefits from the same or, given the time constraint at hand, even better support from European coastal countries. Moreover, the sooner the supportive measures will occur, the higher the operating capacity will be. As seen with the sensitivity analysis, a five-year delay can lead to almost a 50 % decrease in the operating capacity in 2050.

The growth of the offshore wind sector should be taken as an example in terms of support schemes, but the marine energy sector can learn from previous misconceptions. In particular a reduction of delays between the establishment of a policy and when it is applied to a project and the increased speed of permitting and consenting will be critical. At the European level and for some European countries, the first positive developments are visible (European marine energy targets, European initiative to standardize and fasten permitting procedures, UK's contract for difference on tidal energy, commitments of the Portuguese and Spanish government, etc.). Overall, the marine energy sector shows great potential to support the European and global climate targets.

Data availability

Zenodo. European offshore wind farms and marine energy deployments. DOI: 10.5281/zenodo.7938413.

This project contains the following underlying data:

- Offshore_wind_farm_european_deployements.xlsx (European offshore wind farms dataset used to forecast the development of marine energy in Europe in the upcoming three decades).
- Tidal_Energy_Converters_European_deployements.xlsx (Tidal energy converter deployments in Europe dataset used to forecast the development of marine energy in Europe in the upcoming three decades).
- Wave_Energy_Converters_European_deployements.xlsx (Wave energy converter deployments in Europe dataset used to forecast the development of marine energy in Europe in the upcoming three decades)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgements

We would like to thank OEE for providing their LCoE dataset and their ocean energy project database.

Appendix

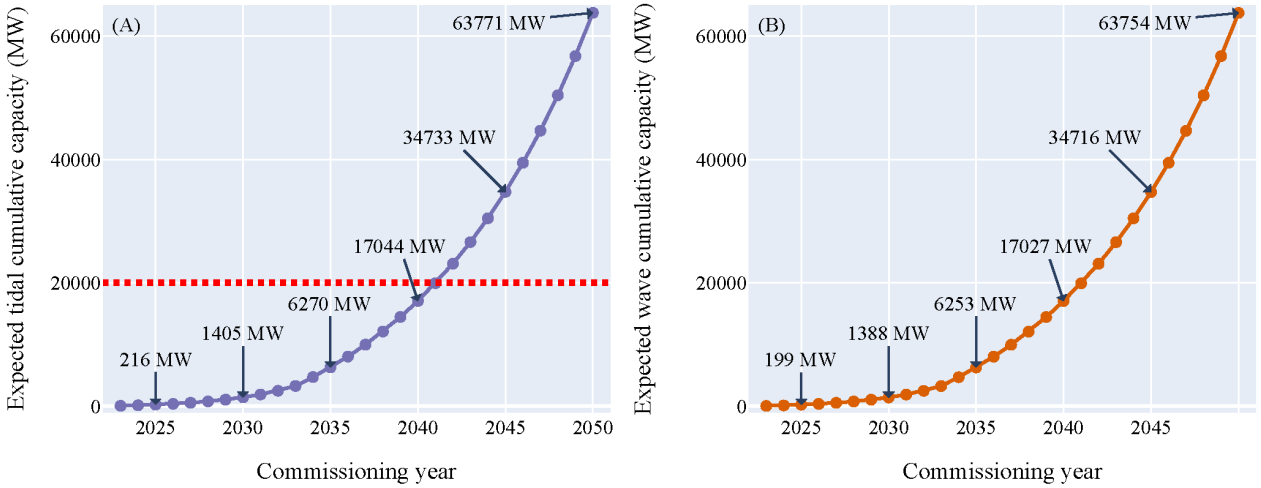


Figure 10. Expected tidal and wave cumulative capacities according to the best case scenario using the growth curve model. (**A**) Tidal - (**B**) Wave Page

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Open Peer Review

Current Peer Review Status: ? ✓ ? ? ?

Version 2

Reviewer Report 12 April 2025

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✓ **Christian Breyer**
School of Energy Systems, LUT University, Lappeenranta, Finland

Thanks for the revised manuscript. The very comprehensive revisions made a substantially improved manuscript.
Only one new comment remains: p. 9, 3rd paragraph: the potential for Europe according to Satymov et al. (2024) is 4.5 TW (see Supplementary 2, tab 2050, cell Y6), not the used 50 TW. With that single number polishing all should be fine.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: renewable energy, energy systems, energy transition, ocean energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 04 March 2025

https://doi.org/10.21956/openreseurope.19897.r50919

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? **Alain Ulazia Manterola**
University of the Basque Country (UPV/EHU), Gipuzkoa-Eibar, Spain

This work studies LCOE of marine energies (wave and tidal) in analogy to offshore wind, to project it to future decades according to the learning curve presented by wind turbines in the past.

Every analogy can be dangerous, and the possible weakness of this analogy should be also

analized, within the limitations of the work.
The presented python code for fitting the curve should be improved the consider confidence intervals of the prediction. Similarly, a relative error should be assigned to the prediction.
Not only the fitting process, the input data also show an intrinsic uncertainty and this should be considered in the final prediction range.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: resource assessment for marine energies, data science, climate models, reanalysis

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 19 February 2025

https://doi.org/10.21956/openreseurope.19897.r50470

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?

Damon Howe
University of Tasmania, Sandy Bay, Australia

The manuscript presents a methodology and analysis for the potential contributions that wave and tidal energy can make in the European renewable energy mix given similar growth and

development trends to fixed-bottom offshore wind.

General comments:
The manuscript could do with a final proof-read for grammar and clarity as there were some instances where sentence structure did not help to support the arguments being made. However, overall the manuscript followed a logical flow.

Further details need to be provided around the application of the offshore wind trends to the wave and tidal predictions. There is a lack of discussion around the limitations of the modelling.

Introduction:
- Depending on the target audience of the manuscript, it might be worthwhile to define (in simplistic terms) what the metric of LCOE measures.
- A question must be asked regarding the use of the capacity growth related to bottom-fixed offshore wind being applied to tidal, and particularly wave in order to provide sufficient data. While these ORE sectors do share many similarities, as mentioned, one major distinction which differentiates the sectors, and has subsequent impact on metrics such as learning rates, is the lack of technological convergence for wave energy (tidal to a lesser degree). Offshore wind is dominated by HAWTs, where wave energy has yet to converge (which also raises the question, is a one-size-fits-all approach best?). I am wondering whether this complexity has been considered in the modelling? If so, what assumptions have been made?

Methods:
- Was the exponential growth curve derived from fixed offshore wind directly transferred to wave and tidal? Or were the coefficents in Equation 1 individually derived for each respective ORE sector?
- In Equation 6, was the growth rate, r, defined as that of the offshore wind, and then subsequently applied to wave and tidal? This is still somewhat unclear in the methodology description, and would relate to the previous points made.
- A section should be included to address any limitations/simplifications/assumptions present in the two models.

Discussion and Conclusions:
- More details required about main assumption, how likely is this given that offshore wind is now dominating the market?

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Offshore renewable energy, particularly wave energy.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 18 February 2025

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?

Abel Arredondo Galeana
University of Strathclyde, Glasgow, UK

This paper addresses the very relevant topic of forecasting the cumulative capacity and reduction in LCOE of marine renewables towards 2050. The paper uses the growth profile of bottom fixed offshore wind energy to derive cumulative capacity growth coefficients to be applied to tidal and wave energy. Then, the LCOE is predicted based on the predicted growth of the tidal and wave energy sector.

Naturally, the approach considered in this work could have certain limitations. For example, the fact that wave energy has not converged to one type of device, as offshore wind did, or the fact that wave energy addresses floating technology and not bottom fixed. Tidal energy, although more similar to offshore wind in terms of device, operates in a submerged manner, and in general, close to seabed or near the water surface. Furthermore, different political, warfare, climate or other type of global event, can affect the growth patterns observed in previous decades. Hence, these limitations should be mentioned in the discussions of the paper.

Nonetheless, novel and creative approaches are needed to predict the growth and LCOE reduction of tidal and wave energy, because growth and cost predictive models are of interest to all the relevant stakeholders to meet net zero targets. Furthermore, the paper addressed already two high quality peer reviews in the previous round. Therefore, I recommend the paper for indexing subject to the following minor reviews:

Introduction:

- Fix typo: salinity grandient > salinity gradient

- "positive policy developments in the ranging from the innovation fund and Horizon Europe program" > remove "in the"
- "Only a few," > missing verb >"Only a few have attempted to include them,..."
- "to have more energy system reports, including ocean energy in a reliable way," > insert comma

Methods:
Tidal energy:

- I would note here that most of the examples considered are for fixed bottom tidal turbines and examples of floating tidal turbines are not considered. Possibly discuss the case of Orbital Marine Power that have deployed 2 MW in 2021, as discussed in the reference: *D. R. Noble, K. Grattan, and H. Jeffrey, 'Future economic potential of Tidal Stream & Wave Energy in Scotland', The University of Edinburgh, Jan. 2025 for possible benchmark comparison cases.*
- Table 1 seems very asymmetric in terms of tidal developers. Although only these three developers were considered, I would include a few more developers here. See for example Table 1 of [Ref 1].

Wave energy:

- For the wave sector – 2020 was established as the year were the sector entered a precommercial scale. > I suggest making a note here to mention that wave energy was pioneered in the 1970s, and has been around even before tidal turbines. However, policy changes and the simultaneous growth of wind power delayed the sector, and arguably, the lag-phase for wave energy could be much longer than what this current paper predicts.
- Maybe worth motioning here the case of Mocean energy, which has been successfully supported by Wave Energy Scotland to carry out a large-scale demonstrator.

Additional notes:

- Sensitivity analysis - Figure 7c seems to have only one curve as opposed to Figure 7a, 7b and 7d. Please check.
- Figure 8 – Please define acronyms used for each country. For example, FI, IE, SE are not defined in the manuscript.

Discussion:

- "Following the offshore Following the offshore wind growth, intermediate values between 46 and 58 MW in 2025 and between 323 and 594 MW in 2030 are realistically achievable." – Please clarify that this statement refers to tidal energy as observed in Fig. 3.
- Pg 13 - Please change "more faster" to "faster"

References

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Marine renewables; Tidal energy; Wave Energy; Offshore renewables

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Version 1

Reviewer Report 24 October 2023

https://doi.org/10.21956/openreseurope.17180.r33209

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?

Christian Breyer
[1] School of Energy Systems, LUT University, Lappeenranta, Finland
[2] School of Energy Systems, LUT University, Lappeenranta, Finland

The manuscript presents an investigation of scenarios on how ocean energy can be scaled up in Europe using learnings from wind offshore.

Main items:

- How the capacity of tidal and wave is linked to LCoE (as shown in Tab. 2) remains unclear. This gap needs to be filled. This gap may be larger, as directly or at least indirectly the learning rate seems to be required, while this aspect is not addressed in the paper so far.

- It may be supportive to highlight the existing research gap in energy system studies that often ignore wave and tidal power, as this leads to a lower awareness of the existing options.

- More scientific literature in the field of research helps for providing more context.

In the following you find all comments in detail, while most are smaller items

Abstract:
In the Results section of the Abstract you refer to targets of the European Commission and link then to European coastal countries. Are the 'European coastal countries' limited to the member states of European Union? There is a large potential in the UK, while the UK does not belong to EU-27, and thus, the UK cannot contribute to the targets of the EC. Wording clarification may be helpful.

Keywords:
Are 'wave power' and 'tidal power' more clear to highlight the electricity harvesting aspect of the more general term of 'wave' and 'tidal'?

Introduction:
1st paragraph: wave and tidal are the most advanced ocean energy technologies, next to offshore wind, better to expand the wording for inclusion of offshore wind. More literature references for the wave and tidal potential may be helpful. Gunn and Stock-Williams (2012[1]) find up to 18,500 TWh and Mork *et al*. find up to 26,100 TWh (https://doi.org/10.1115/OMAE2010-20473). Nevertheless, the study is on Europe, thus, the potential for wave power and tidal power in Europe would be of particular interest. You may also mention the potential of offshore wind, so that the three technologies you focus on in the paper are all presented with their potential in Europe.

2nd paragraph: better to clarify the targets for ocean energy in addition to offshore wind, as the latter may have separate targets, given the numbers presented.

4th paragraph: it may be worth mentioning whether in other parts in the world, in particular in Asia, one can observe progress in the deployment of wave and tidal power. Experience shows that a major breakthrough in other world regions may induce strong development in other regions as well. Please check the 4th sentence for the grammar.

5th paragraph: 'forecast' typically describes periods up to 5 not more than 10 years, while longer periods in the order of decades may be better described by 'projection' for reflecting a higher degree of uncertainty.

It would be interesting to add one paragraph on literature on the role of wave and tidal power for Europe. Are the two technologies mentioned in WEO reports of the IEA for Europe? Is there scientific literature on the role of the two technologies, for Europe, or for single countries? For the IEA WEO I checked it but only global numbers are reported in recent reports, no numbers for Europe. On a country basis at least a recent study for the UK, which found up to 42 GW installed capacity in the UK and Ireland until 2050 (Alvarez-Silva *et al.*, 2016[3]), this may be valuable for this research as it documents a value add of wave power for the energy transition from an energy system perspective. In the energy [r]evolution scenario of Greenpeace one can find 53 GW of ocean energy installed in OECD Europe by 2050 (https://www.greenpeace.org/static/planet4-canada-stateless/2018/06/Energy-Revolution-2015-Full.pdf; Tab. 13.4.18), which may be a valuable reference, given the low coverage of ocean energy in energy scenarios. More related research may be quite helpful for the aims of the paper.

Methods:
There is an unexpected break in the flow from the 2nd to the 3rd paragraph (from wind to wave/tidal). Having the section headline expanded to 'Starting values and years for wave and tidal' may ease that a bit.

p. 4, 1st paragraph: 'power purchase agreement' is used again as a word, while the abbreviation PPA was introduced earlier in this section. Another example is CAGR what's again used in the long version on the next page, while the abbreviation was introduced before. Please check for all abbreviations that they are used consequently, once the abbreviation was introduced.

Table 1: Sweden is abbreviated with 'SW', while the typical convention should be 'SE', please check for the entire manuscript.

p. 4 right column, 3rd paragraph: 'bad correlation' may be better as 'poor' or 'weak' correlation.

p. 5, 1st paragraph: three exponential functions are mentioned. I may be helpful to mention the three phases so that it is explicitly clear to what 'three' refers.

p. 5 (and others): please check all used abbreviations whether they are introduced. For instance OEE and ORE appears, while this should be abbreviations.

p. 5/6: section on LCoE is important for the entire paper. Please introduce the formula for LCoE.

p. 6 left column bottom: "... the values given in the table." Which table? Please refer explicitly to the table referred to in the paper.

p. 6: Tab. 2 is not referenced in the text, please embed it into the text. Where are the starting values for tidal and wave LCoE for 1 MW from? These are among the most important references, as the derived costs are directly linked to these starting values. Please discuss the validity of these starting values, as they have a very strong impact on the results. You may consider a sensitivity for these values. The link of LCoE to the capacity remains unclear. What formula links LCoE to the capacities? Is a learning rate applied? If so, which value(s) and based on what reference? The Tab. 2 seems to be central, while the impact of the capacity on the LCoE remains unclear.

Results and analysis:
p. 8, 3rd paragraph: it may be worth checking additional literature for the wave power potential of 95 GW in Europe. There is unpublished research with much higher values (more than an order of magnitude more, however, for entire Europe, thus, explicitly including the UK and Norway), therefore, other literature may also find higher values. Please also clarify for the wave power potential for Europe, whether entire Europe (incl. the UK, Norway, Iceland, etc.) is meant, or EU-27. For the case of ocean energy this makes a considerable difference. The best may be to clarify across the entire paper whether EU-27 or entire Europe is meant, whenever the term 'Europe' is used. In the right column it is mentioned that the UK is assumed to contribute to the EU targets. That most important assumption is better mentioned earlier in the paper, when the term 'Europe' is used for the first time in the context of this paper.

p. 8, section European targets: please add per additionally mentioned category (salinity gradient,

OTEC, floating PV) at least one scientific reference. Good literature may be (please check for yourself): Alvarez-Silva *et al.* (2016[3]); Langer *et al.* (2020[4]); Shi *et al.* (2023[5]); Breyer *et al.* (2023[6]); however, at least OTEC seems not to be that attractive for Europe given the tropical water temperature required, while the Mediterranean may develop towards that directly due to climate change, unfortunately.

p. 8, Fig. 5: link to the (new) methods how the LCoE decline over time. What is the learning rate? How is the cost decline calculated? It's not clear in the paper how this is calculated.

p. 10, 1st paragraph: 'deployment' may be better suited then 'journey'.

p. 10, section offshore wind: it may be helpful to better explain what 'MetOcean' shall be.

p. 10, section 'Best case scenario'. It may be helpful to introduce the 'Best case scenario' already in the Methods section, so that readers are prepared on different scenarios or respective variations. That may be done best in a paragraph on scenarios to be considered.

Discussion and conclusion:
p. 10, 1st paragraph of the section. The term 'net zero emission' links nicely to the same from the Introduction. It may be helpful to expand the section on 'net zero emissions' a bit as this is clearly set in the European Green Deal. Different pathways are possible to reach that aim, while highly renewable energy system transition options may be most likely, also cost-wise. This and a review on comparable studies was published here (Breyer *et al.*, 2022[7]), where wave and tidal power is missing in almost all studies, and that research gap may be documented with this overview, while the previously mentioned paper on the UK clearly indicates that latest research may be able to close this gap. In that regard, it may be helpful that at least for three European islands wave and tidal power systems had been investigated as part of a highly renewable energy system and published in scientific articles (Meschede *et al.*, 2022[8]; see Tab. 5), as detected for the cases of El Hierro, Faroe, and Sardinia. Not sure whether this may be a helpful indication of upcoming wave and tidal power systems for the benefit of the paper, as island energy systems.

You may mention, that wave and tidal power could also develop faster than wind offshore, since many challenges (such as grid connection, O&M, harbour logistics, etc.) have been fixed for wind offshore, thus, wave and tidal power can build on that, which should enable a faster growth potential.

References:
Please expand the references across the paper for more scientific references in scientific journals. The present list of references lists 16 references, thereof only one is from a scientific journal. Any share of 25%, better 33% up to 50% of peer-reviewed journal references should be a target to provide a broader context to the scientific literature in the field of renewables, the energy transition, in particular in Europe, ocean energy in general, but in particular for wave power and tidal power, and their link to offshore wind.

References
1. Gunn K, Stock-Williams C: Quantifying the global wave power resource. *Renewable Energy*. 2012; **44**: 296-304 Publisher Full Text
2. Diesing P, Bogdanov D, Satymov R, Child M, et al.: Offshore versus onshore: The

underestimated impact of onshore wind and solar photovoltaics for the energy transition of the British Isles. *IET Renewable Power Generation*. 2023; **17** (13): 3240-3266 Publisher Full Text
3. Alvarez-Silva O, Osorio A, Winter C: Practical global salinity gradient energy potential. *Renewable and Sustainable Energy Reviews*. 2016; **60**: 1387-1395 Publisher Full Text
4. Langer J, Quist J, Blok K: Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda. *Renewable and Sustainable Energy Reviews*. 2020; **130**. Publisher Full Text
5. Shi W, Yan C, Ren Z, Yuan Z, et al.: Review on the development of marine floating photovoltaic systems. *Ocean Engineering*. 2023; **286**. Publisher Full Text
6. Breyer C, Oyewo A, Kunkar A, Satymov R: Role of Solar Photovoltaics for a Sustainable Energy System in Puerto Rico in the Context of the Entire Caribbean Featuring the Value of Offshore Floating Systems. *IEEE Journal of Photovoltaics*. 2023. 1-7 Publisher Full Text
7. Breyer C, Bogdanov D, Ram M, Khalili S, et al.: Reflecting the energy transition from a European perspective and in the global context—Relevance of solar photovoltaics benchmarking two ambitious scenarios. *Progress in Photovoltaics: Research and Applications*. 2022. Publisher Full Text
8. Meschede H, Bertheau P, Khalili S, Breyer C: A review of 100% renewable energy scenarios on islands. *WIREs Energy and Environment*. 2022; **11** (6). Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: renewable energy, energy systems, energy transition, ocean energy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 08 Aug 2024

Benjamin Lehner

Thank you Christian for this detailed and valuable feedback and excuses for the delayed reply. We will upload the latest version in the coming days but please find below already our answers to your remarks (*in cursive)* one by one with the replies underlined. CB.1.1: In the Results section of the Abstract you refer to targets of the European Commission and link then to European coastal countries. Are the 'European coastal countries' limited to the member states of European Union? There is a large potential in the UK, while the UK does not belong to EU-27, and thus, the UK cannot contribute to the targets of the EC. Wording clarification may be helpful.
BL 1.1: Thank you for the comment, we agree that the differentiation between Europe / EU-27 / EU-27 plus associated countries are not clear enough in the paper. For clarity we added the following subsentence (bold) in the Abstract-results part. "According to both models, the 40 GW 2050 target for ocean energy set by the European Commission in 2020 could be reached if European coastal countries, including associated countries to the EU-27, adopt supportive policies for both technologies immediately." The associated countries include Norway and the UK. CB 2.1: 1st paragraph: wave and tidal are the most advanced ocean energy technologies, next to offshore wind, better to expand the wording for inclusion of offshore wind. More literature references for the wave and tidal potential may be helpful. Gunn and Stock-Williams (2012[1]) find up to 18,500 TWh and Mork et al. find up to 26,100 TWh (https://doi.org/10.1115/OMAE2010-20473). Nevertheless, the study is on Europe, thus, the potential for wave power and tidal power in Europe would be of particular interest. You may also mention the potential of offshore wind, so that the three technologies you focus on in the paper are all presented with their potential in Europe.
BL 2.1: We normally use the definition of Ocean Energy Europe to define wave, tidal, salinity gradient & OTEC as Ocean Energy. Offshore wind and offshore solar are separate in this definition. To avoid any misunderstanding we are differentiating between "Offshore Renewable Energy" and "Ocean Energy" throughout the paper. We also added the additional references and split up the potential in all three sources. We stayed with the global potential as the sources for Europe are not fully conclusive on the total potential. CB 2.2: 2nd paragraph: better to clarify the targets for ocean energy in addition to offshore wind, as the latter may have separate targets, given the numbers presented. BL 2.2: Thank you for pointing this out. We added the data and changed the flow of the paragraph to explain why we are explaining LCoE and capacity at all. We also added the offshore wind targets for consistency and in relationship to Christian's comment. CB 2.3 4th paragraph: it may be worth mentioning whether in other parts in the world, in particular in Asia, one can observe progress in the deployment of wave and tidal power. Experience shows that a major breakthrough in other world regions may induce strong development in other regions as well. Please check the 4th sentence for the grammar. BL 2.3: We added the proposed description on funding mechanisms in the EU, UK and US. We also added Asian countries with a strong dedication for offshore renewable energy. We also improved the writing of the paragraph. CB 2.4: It would be interesting to add one paragraph on literature on the role of wave and tidal power for Europe. Are the two technologies mentioned in WEO reports of the IEA for Europe? Is there scientific literature on the role of the two technologies, for Europe, or for single countries? For the IEA WEO I checked it but only global numbers are reported in recent reports, no numbers for Europe. On a country basis at least a recent study for the UK, which found up to 42 GW installed capacity in the UK and Ireland until 2050 (Alvarez-Silva et al., 2016[3]), this may be valuable for this research as it documents a value add of wave power for the energy transition from an energy system

perspective. In the energy [r]evolution scenario of Greenpeace one can find 53 GW of ocean energy installed in OECD Europe by 2050 (https://www.greenpeace.org/static/planet4-canada-stateless/2018/06/Energy-Revolution-2015-Full.pdf; Tab. 13.4.18), which may be a valuable reference, given the low coverage of ocean energy in energy scenarios. More related research may be quite helpful for the aims of the paper.. BL 2.4: We addressed the novelty comment from Shona and Energy system from Christian together, referring to current negligence on wave and tidal in most energy system reports. Additionally, 25 references are added of which 11 are from scientific journals. CB 3.6: There is an unexpected break in the flow from the 2nd to the 3rd paragraph (from wind to wave/tidal). Having the section headline expanded to 'Starting values and years for wave and tidal' may ease that a bit. BL 3.6: Great suggestion, we adopted that change. CB 3.7: p. 4, 1st paragraph: 'power purchase agreement' is used again as a word, while the abbreviation PPA was introduced earlier in this section. Another example is CAGR what's again used in the long version on the next page, while the abbreviation was introduced before. Please check for all abbreviations that they are used consequently, once the abbreviation was introduced. p. 5 (and others): please check all used abbreviations whether they are introduced. For instance OEE and ORE appears, while this should be abbreviations. BL 3.6: Thanks for pointing out those inconsistencies, we adopted that change. CB 3.8: Table 1: Sweden is abbreviated with 'SW', while the typical convention should be 'SE', please check for the entire manuscript. p. 4 right column, 3rd paragraph: 'bad correlation' may be better as 'poor' or 'weak' correlation. BL 3.8: We adopted those changes. CB 3.9: p. 5, 1st paragraph: three exponential functions are mentioned. It may be helpful to mention the three phases so that it is explicitly clear to what 'three' refers. BL 3.9: We added numbering to make the link clearer. CB 3.10: p. 5/6: section on LCoE is important for the entire paper. Please introduce the formula for LCoE. BL 3.10: The fit to the LCoE formula was added insterad of the formula as no direct LCoE calculation was done by us. CB 3.11: p. 6 left column bottom: "... the values given in the table." Which table? Please refer explicitly to the table referred to in the paper. p. 6: Tab. 2 is not referenced in the text, please embed it into the text. Where are the starting values for tidal and wave LCoE for 1 MW from? These are among the most important references, as the derived costs are directly linked to these starting values. Please discuss the validity of these starting values, as they have a very strong impact on the results. You may consider a sensitivity for these values. The link of LCoE to the capacity remains unclear. What formula links LCoE to the capacities? Is a learning rate applied? If so, which value(s) and based on what reference? The Tab. 2 seems to be central, while the impact of the capacity on the LCoE remains unclear. BL 3.11: We added the reference to table 2 and explicitly referred to the table as indicated above. The table as well as text now includes the calculated learning rates from the OEE values. The numbers by OEE are not supported by specific learning rates but the table contains the values re-evaluated from the provided table. This should provide more clarity on the source as well as the general meaning of the values. CB 4.3: p. 8, 3rd paragraph: it may be worth checking additional literature for the wave power potential of 95 GW in Europe. There is unpublished research with much higher values (more than an order of magnitude more, however, for entire Europe, thus, explicitly including the UK and Norway), therefore, other literature may also find higher values. Please also clarify for the wave power potential for Europe, whether entire Europe (incl. the UK, Norway, Iceland, etc.) is meant, or EU-27. For the case of ocean energy this makes a considerable difference. The best may be to clarify across the entire paper whether EU-27 or entire Europe is meant, whenever the term 'Europe' is used. In the right column it is

mentioned that the UK is assumed to contribute to the EU targets. That most important assumption is better mentioned earlier in the paper, when the term 'Europe' is used for the first time in the context of this paper. p. 8, section European targets: please add per additionally mentioned category (salinity gradient, OTEC, floating PV) at least one scientific reference. Good literature may be (please check for yourself): Alvarez-Silva et al. (20163); Langer et al. (20204); Shi et al. (20235); Breyer et al. (20236); however, at least OTEC seems not to be that attractive for Europe given the tropical water temperature required, while the Mediterranean may develop towards that directly due to climate change, unfortunately. BL 4.3: The reference of Mork et al was added to increase the range of values provided. Satymov et al. does not include a regional breakdown of energy potential for European regions and was not added. We also tried to clarify better throughout the paper which "Europe" we are referring to (EU-27 vs EU+associated countries) - see comment 1.1. CB 4.4: p. 8, Fig. 5: link to the (new) methods how the LCoE decline over time. What is the learning rate? How is the cost decline calculated? It's not clear in the paper how this is calculated. BL 4.4: See comment 3.11 - Based on the values for LCOEs published by OEE the learning rates have been re-calculated. A table on these values has been added showing also these re-calculated LR values. CB 4.5: p. 10, 1st paragraph: 'deployment' may be better suited then 'journey'. p. 10, section offshore wind: it may be helpful to better explain what 'MetOcean' shall be. BL 4.5: We implemented those changes and replaced MetOcean with offshore measurement campaigns. CB 4.6: p. 10, section 'Best case scenario'. It may be helpful to introduce the 'Best case scenario' already in the Methods section, so that readers are prepared on different scenarios or respective variations. That may be done best in a paragraph on scenarios to be considered. BL 4.5: We added a subsection to the methods that introduces all considered scenarios CB 5.2: p. 10, 1st paragraph of the section. The term 'net zero emission' links nicely to the same from the Introduction. It may be helpful to expand the section on 'net zero emissions' a bit as this is clearly set in the European Green Deal. Different pathways are possible to reach that aim, while highly renewable energy system transition options may be most likely, also cost-wise. This and a review on comparable studies was published here (Breyer et al., 20227), where wave and tidal power is missing in almost all studies, and that research gap may be documented with this overview, while the previously mentioned paper on the UK clearly indicates that latest research may be able to close this gap. In that regard, it may be helpful that at least for three European islands wave and tidal power systems had been investigated as part of a highly renewable energy system and published in scientific articles (Meschede et al., 20228; see Tab. 5), as detected for the cases of El Hierro, Faroe, and Sardinia. Not sure whether this may be a helpful indication of upcoming wave and tidal power systems for the benefit of the paper, as island energy systems. You may mention, that wave and tidal power could also develop faster than wind offshore, since many challenges (such as grid connection, O&M, harbour logistics, etc.) have been fixed for wind offshore, thus, wave and tidal power can build on that, which should enable a faster growth potential. BL 5.1: We added additional publications and expanded upon this in the discussion section. Apologies again for the delay in our reply and we reamin to further improve parts of the paper if needed. Thanks a lot for reviewing this work and helping us improving it.

Competing Interests: No competing interests were disclosed.

Reviewer Report 13 July 2023

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Shona Pennock
[1] School of Engineering, The University of Edinburgh, Edinburgh, UK
[2] School of Engineering, The University of Edinburgh, Edinburgh, UK

This paper details an analysis of the potential deployment and cost reduction trajectories for wave and tidal technologies, based on historical wind deployment trajectories and industry-recognised ocean energy cost reduction trajectories from Ocean Energy Europe. This is important and interesting work, and was a pleasure to read. The paper is well structured, easy to read and understand, and the figures are also clear and well presented.

As a general comment, this paper could do with a proof read by a native english speaker for grammar and wording choice. There are some small errors throughout, such as prepositions out of place. To name one example, the third paragraph should read 'By the beginning..' and not 'By beginning'. These small errors do not affect the reader's ability to understand the work, however.

Some further suggestions for more specific changes and improvements are below:

Introduction:

- When discussing the potential LCoE of wave and tidal in the introduction, it could be useful to frame this in context, e.g. of the current LCoE of offshore wind, or compared to average day-ahead electricity prices over the last decade. A reader with little knowledge of these might stuggle to understand the importance of further cost reduction for ocean energy. Similarly, it might also be useful to reference the current estimated LCoE of wave and tidal in the introduction section, to give some initial context.

- In the introduction you state that there have been positive policy developments in the EU, US, and UK. It would be good to give a couple of brief examples of these for the reader, e.g. the millions spent in innovation funding for ocean energy through Horizon Europe, the market-pull support schemes in the UK including the Renewables Obligation and Feed-in Tarriffs with Contracts for Difference.

- There needs to be some words in the introduction to explain the novelty of this work, and what it adds to the existing literature. I'd also recommend that some more scientific journal papers are referenced at this point.

Methods:

- For repeatability, the offshore wind database used for this analysis needs to be referenced in the first paragraph of the methods section. The ocean energy europe database should also be referenced in the third paragraph.

- It would add some clarity for the reader to have some kind of flow chart, or numbered list to explain the key steps of the methodology, before explaining each stage further in the sub-sections.

- In equation 1 I think the Pcum,0 should be replaced by Py,0 - if I have understood this correctly.

- For equation 2, I was unsure why 'y' is being used to denote the capacity figure, when 'P' is used to denote installed capacity in equation 1. From the explanatory text it reads as if the nomeclature is inconsistent between these two equations. It also seems that 'q' is then being used for capacity in equations 3-6.

- It seems inconsistent that five-year intervals were chosen for the doubling time model, when ten-year intervals were chosen for the growth model. Some further explanation is needed to justify this.

- In figure 1, 'a', 'b' and 'N' should be defined in the figure caption so that a reader can understand the figure more easily at a glance.

Results:

- It would be clearer in figures 1, 2 and 3, to label the two separate graphs as (a) and (b), rather than (1) and (2), so as not to confuse with the figure number. Likewise with figures 6, 7, and 9.

- In the caption for figure 4, it would be useful to specify that this is the percentage of the targets fulfilled specifically by wave and tidal stream technologies.

- In figure 6, has this sensitivity been undertaken for the wave/tidal results, or the more general model, extrapolating from the offshore wind figures? It would be useful to have some text to discuss how this sensitivity analysis would be reflected in the wave and tidal technology results (e.g. by how much would the 2030 LCOE targets be delayed for each of these sensitivity cases).

Discussion/conclusion:

- Another key assumption that is worth discussing is the cost reduction trajectory for wave and tidal technologies. While this is based on the best current estimations of the sector, as presented by Ocean Energy Europe, there will be a great deal of uncertainty associated with these due to the early development stage of the sector. This cost reduction could also be very technology specific, for example to different wave or tidal device designs. The ability to achieve this cost reduction is also highly sensitive to the available policy support, such as innovation funding.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Economics of innovation, ocean energy techno-economics, ocean energy technologies

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 08 Aug 2024

Benjamin Lehner

Thank you Shona for this detailed and valuable feedback and excuses for the delayed reply. We will upload the latest version in the coming days but please find below already our answers to your remarks (*in cursive)* one by one with the replies underlined.

SP 2.2:When discussing the potential LCoE of wave and tidal in the introduction, it could be useful to frame this in context, e.g. of the current LCoE of offshore wind, or compared to average day-ahead electricity prices over the last decade. A reader with little knowledge of these might struggle to understand the importance of further cost reduction for ocean energy. Similarly, it might also be useful to reference the current estimated LCoE of wave and tidal in the introduction section, to give some initial context.
BL 2.2: Thank you for pointing this out. We added the data and changed the flow of the paragraph to explain why we are explaining LCoE and capacity at all. We also added the offshore wind targets for consistency and in relationship to Christian's comment.
SP 2.3 In the introduction you state that there have been positive policy developments in the EU, US, and UK. It would be good to give a couple of brief examples of these for the reader, e.g. the millions spent in innovation funding for ocean energy through Horizon Europe, the market-pull support schemes in the UK including the Renewables Obligation and Feed-in Tariffs with Contracts for Difference. BL 2.3: We added the proposed description on funding mechanisms in the EU, UK and US. We also added Asian countries with a strong dedication for offshore renewable energy. We also improved the writing of the paragraph.

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5th paragraph: 'forecast' typically describes periods up to 5 not more than 10 years, while longer periods in the order of decades may be better described by 'projection' for reflecting a higher degree of uncertainty.
BL 2.4: We addressed the novelty comment from Shona and Energy system from Christian together, referring to current negligence on wave and tidal in most energy system reports. Additionally, 25 references are added of which 11 are from scientific journals. SP 3.1: For repeatability, the offshore wind database used for this analysis needs to be referenced in the first paragraph of the methods section. The ocean energy europe database should also be referenced in the third paragraph.
BL 3.1: We added the offshore wind database but sadly do not have permission to make the data from OEE public. SP 3.2 It would add some clarity for the reader to have some kind of flow chart, or numbered list to explain the key steps of the methodology, before explaining each stage further in the sub-sections. BL 3.2: We agree with the reviewer. A flow chart summarizing the key steps taken to build the presented model is added to the beginning of the methods section. Each step is then further elaborated in sub-sections. Key steps methodology added:

1. Data acquisition on bottom-fixed offshore wind farms and setting the reference year.
2. Data acquisition of wave and tidal projects in Europe
    1. filtering out disappeared and prolonged hibernating projects
    2. Determine the pre-commercial start years for wave and tidal
3. Fit growth curve based on the installed cumulative bottom-fixed offshore wind
    1. Exponential fit based on cumulative capacity
        1. Three different phases: lag, kickoff and growth
    2. Doubling time curve fit
        1. five different phases
4. Apply growth curves to wave and tidal
5. LCOE forecast based on predicted wave and tidal growth

SP 3.3 In equation 1 I think the Pcum,0 should be replaced by Py,0 - if I have understood this correctly. For equation 2, I was unsure why 'y' is being used to denote the capacity figure, when 'P' is used to denote installed capacity in equation 1. From the explanatory text it reads as if the nomenclature is inconsistent between these two equations. It also seems that 'q' is then being used for capacity in equations 3-6. BL 3.3: We changed "Pcum,0" by "Py,0" in the text. Therefore, "Py" stands for the cumulative capacity at the year "y". We also replaced "q" by "P" in equations 3 to 6 to stay consistent in the nomenclature. Regarding equation 2, we used "y" and not "P" because it is a general formula which can be applied to numerous fields. SP 3.4 It seems inconsistent that five-year intervals were chosen for the doubling time model, when ten-year intervals were chosen for the growth model. Some further explanation is needed to justify this. BL 3.4: Regarding the growth model, we wanted to show that there were three different phases during the development of the offshore wind sector: the lag phase with only few pilot projects, the kick-off phase with the commissioning of the first commercial farms and the growth phase with the quick expansion of the offshore industry. We wanted to apply those three different phases to the

tidal energy and wave energy industry. Regarding the doubling time model, we tried to find the best balance between a high coefficient of determination and a good correlation with the data points. After trying different intervals, it appeared that a 5-year interval was the best compromise. SP 3.5 In figure 1, 'a', 'b' and 'N' should be defined in the figure caption so that a reader can understand the figure more easily at a glance. BL 3.5: We added those definitions to the figure caption. SP 4.1: It would be clearer in figures 1, 2 and 3, to label the two separate graphs as (a) and (b), rather than (1) and (2), so as not to confuse with the figure number. Likewise with figures 6, 7, and 9. In the caption for figure 4, it would be useful to specify that this is the percentage of the targets fulfilled specifically by wave and tidal stream technologies. BL 4.1: We added those changes. SP 4.2: In figure 6, has this sensitivity been undertaken for the wave/tidal results, or the more general model, extrapolating from the offshore wind figures? It would be useful to have some text to discuss how this sensitivity analysis would be reflected in the wave and tidal technology results (e.g. by how much would the 2030 LCOE targets be delayed for each of these sensitivity cases). BL 4.2: This sensitivity analysis has only been applied to the starting capacity and/or starting year of wave and tidal, as their starting value and year are not clearly identifiable, both being in a pre-commercial stage. No sensitivity run on the reference year/capacity of offshore wind has been performed, as its starting year and capacity is more identifiable (the first offshore wind array commissioned). SP 5.1: Another key assumption that is worth discussing is the cost reduction trajectory for wave and tidal technologies. While this is based on the best current estimations of the sector, as presented by Ocean Energy Europe, there will be a great deal of uncertainty associated with these due to the early development stage of the sector. This cost reduction could also be very technology specific, for example to different wave or tidal device designs. The ability to achieve this cost reduction is also highly sensitive to the available policy support, such as innovation funding. BL 5.1: Most of the data here is based on OEE and an EU-SCORES report we did on this topic (https://euscores.eu/wp-content/uploads/2022/11/D.7.9-LCOE-Analysis-for-baseline-V3_07.10.2022.pdf) . We are also planning to launch a new report from EU-SCORES soon to further advance this work

Apologies again for the delay in our reply and we reamin to further improve parts of the paper if needed. Thanks a lot for reviewing this work and helping us improving it.

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