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Marine renewables in Energy Systems: Impacts of climate data, generators, energy policies, opportunities, and untapped potential for 100% decarbonised systems

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ABSTRACT

The Energy Transition requires meticulous planning, taking into consideration economic, technical, social, and resource constraints. In Europe ambitious targets have been set for system electrification, however, integrating the potential of marine renewables have not been thoroughly investigated. This study extends the framework of PyPSA-Eur into PyPSA-Eur-MREL that for the first time incorporates all marine renewables, using high resolution datasets, that uncover the potential of marine renewables. Marine renewables are modelled in terms of power estimations, deployment strategies and revised packing density, and expected benefits for 2030, and 2050 across all European Countries are quantified. Higher spatio-temporal data have an immediate impact in estimates, and reduction of energy storage by 73%. Wind energy has a reduced installation capacity by 50%, but the higher fidelity of resource matches production to demand and reduces curtailments up to 60%. System costs with high resolution data are 40% reduced to 160 billion € for a 2030 100% renewable reliant system. The benefits of having more marine renewables are not limited to cost and more efficient demand matching, reduced energy storage, but it also with the area required to decarbonise the system. The results are encouraging and outline the importance and further need for marine renewable energies.

1. Introduction

The latest report of the Intergovernmental Panel on Climate Change (IPCC) underlined the fact that we are close in surpassing the 1.5 °C within the next few years [1]. The ambition to fully decarbonise our energy system, or move to carbon neutral one, has been a long aspiration of several countries. Over the last decades, many models have been developed to assess and evaluate energy and electricity systems, in particular, to better understand and address the challenges related to variable renewable energy system integration. From short-term operation to long-term investment and planning, models have been used to assess the technical feasibility, economic viability, and potential of high sharing renewable energy and electricity systems. They have been further used to identify potential transition and decarbonisation pathways, to provide insights on the necessary steps to decarbonise our energy systems [2].

Economic growth is shown that it has been positively affected by high shares of renewables, as it can enhance and democratise energy access; reduce energy poverty, increase mobility options and accelerate tech-economic development [3–5]. While at the short term, energy prices may slightly increase, in high renewable energy systems the wholesale price of electricity will be reduced, regardless of which variable renewable electricity source is utilised [6]. Of course, an optimal mixture is dependent on local resource utilisation, and high renewable energy penetration does not necessarily grid destabilisation. This means that high resolution modelling is expected to determine the impacts on prices by resource variations [7], mostly concerned with selecting the appropriate year to use data from.

Several studies have shown that the pathways exist, and can provide fully renewable solutions. Hansen et al. [8] reviewed a large number of available literature, which has shown an increase since the mid-2000s. A large number of studies touched upon the feasibility of a 100% system, with different configurations, sometimes including Carbon Capture and/or biomass, that are not classified as renewable energies. The same study also identified gaps in technologies, and hinted that use of high spatio-temporal resolutions may offer some advantages.

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Recently, Breyer et al. [9] looked into the developments, and availability of different Energy System Models (ESM), and the challenges they try to overcome such as system variability/stability, strategies for 100% energy scenarios. The authors highlighted a lack of oversight of raw materials that is often needed, and will be key for the energy transition. There are instances that while the solutions derived by ESM's are cost-effective, will not be material effective, i.e. Lithium extraction limits and PhotoVoltaic (PV) associated issues. This highly detailed study provides an in-depth review and state-of-the-art of ESMs, thoughout their history. Breyer underlined several topics that need to be addressed with the work also providing ample proof disproving the common “myths” that are associated with 100% energy systems, such are high variability and costs.

Of course scepticism is always part of the scientific process, Heard et al. [10] posed arguments for the viability of highly renewable systems. A response to their concerns was provided by Brown et al. [11], which addressed the issues raised and supported the feasibility of 100% Energy Systems. In most studies wind and solar are expected to be a “base” load plant, with local resource availability differentiating the mixture. However, usually marine renewable technologies like wave, tidal and floating wind are not taken into account.

Zappa et al. [12] used the model PLEXOS to consider the question for the feasibility of 100% renewable energy systems by 2050. One of the important findings was that such an approach is possible, but transmission grid reinforcements are necessary. The suggestion is that installed renewable capacities have to be ≥ 1.9 TW, with the grid effectively maintaining the current (2018) level of adequacy. Brown et al. [13] modelled the European energy system showing the feasibility of a high renewable system, with ≥75% in final energy use. The study also indicated interconnectivity between countries will have to increase, but such a scenario can achieve a 95% CO_2 emissions reduction when compared to 1990.

Jacobson et al. [5] developed a roadmap for 139 countries comprised solely on renewable energies, quantified the consequences by displacing fossil and nuclear stations. Technically, all solutions exist that will take us to the new energy era, if all “hidden” externalities of fossil fuels and nuclear, are also included in policy making, it is obvious that minimum intrusive and least dangerous solution for societal sustainability are renewable energies. The study shows that ≈4.6 million deaths/annum can be avoided, due to renewables and a significant reduction in energy poverty can also be expected.

Jacobson [14] further quantified the impacts that can be avoided with 100% renewable Wind-Water-Sun (WWS) systems, concluding that the social costs are reduced almost 91% when compared with the business-as-usual (BAU) energy systems that include fossil fuels. Furthermore, the expected cost of WWS system is 61% lower than that of BAU, with WWS requiring 6.1 trillion \$/year while BAU requires 17.7 trillion \$/year. In terms of expected spatial coverage, 0.65% of land use of the 143 countries was considered.

In terms of wave energy in energy systems, one of the first studies to include wave energy was by Lund 2006 [15] using EnergyPLAN, where a wave energy converter was used in the design of the Danish energy system, including wind onshore, solar and wave energy. The model used hourly 1-year data and ran a sensitivity analysis of power production by the different sources. Results showed that as the energy fraction increased, a system could attain “stability” with wave energy, stabilising variable wind and limited temporal solar production.

Most recently, Keiner et al. [16] examined the Energy System of the Maldives using EnergyPlan, and a point absorber. The study showed that wave power can contribute to regional energy security, with wave power being reliable even at moonsoon seasons, whilst also minimising the need for energy storage. In fact, it can be seen by numerous studies that wave energy is a complementary resource for other renewables, as it reduces the probability of zero occurrences for power due to its reduced variability, whilst maintaining system adequacy with lower requirement of energy storage systems [17–22].

Another element that influences the deployment of renewable generators is the fidelity and spatio-temporal resolution of grid nodes and climate information. Schlachtberger et al. [7] examined the influence of different climate years on mainly wind and solar yielding different capacity factors, thus a different mix for installation, although the system cost saw little change. In the same study, the authors suggest that the sampling rate should not be higher than 3 hours (3 hr), as it will interfere with stability for certain types of renewables.

In terms of grid representation models, often lower fidelity grid models are used, which can lead to non-realistic energy mixes as they ignore congestion, capacity transmissions, curtailments and connectivity issues [23]. These above mentioned elements will become more prevalent as renewable capacity increases, but grid expansion will not keep up the pace [24]. Hence, this can lead to marine renewables not getting enough access to the grid.

Marine renewables are often overlooked in their implementation due to either lack of technical information, or the perception that they are more expensive with regards to more established renewables (such as onshore wind, and solar). Satymov et al. [25] showed that wave energy can have a reduction path that would allow the Levelised Cost of Electricity (LCOE) for 2030 to be ≤ 100 €/MWh and ≤ 50 €/MWh for 2050. The authors explored the potential for wave energy globally, and clearly unveiled that the applicability is not limited only to some countries. Lavidas et al. [26] showed that milder resources are also viable for wave energy converters, and especially after proper resource-location matching, can obtain LCOE values as low as 60 €/MWh. In the same study, the authors also looked into the amortisation periods and linkage to CaPital Expenditure (CAPEX) values, concluding that in the next decade wave energy can reduce its LCOE by at least 10 cents€/kWh.

This study, for the first time evaluates the contribution of marine renewables, to the European Energy System by modelling wave energy converters (WECs), floating wind, tidal energy and floating solar. In addition, the impacts of climate input fidelity are further investigated and with use and introduction of high spatio-temporal datasets, as they prove to be vital for proper deployment considerations. For the first time multiple WECs are incorporated simultaneously into an energy system model, and distributed according to their depth of application - shallow, nearshore and farshore. Furthermore, floating wind is re-configured with state-of-the-art turbines. For all the types of marine renewables we take into account depth considerations (minima and maxima), distance from shore, as well as all periphery costs (i.e. cabling, connection points etc.). Power generation by WECs is done according to wave energy standards, and the power matrix avoids using availability and/or efficiency coefficients, that lead to misleading power estimations. So far, most studies use a non-advisable coefficient based approach i.e. efficient index, cross width ratio, etc. [27].

Another key insight of the study, is the impact of spatial resolution of renewable resources in the deployable potential. As previously mentioned some studies have looked into sampling, and grid nodal resolution, but a key factor that is often overlooked is the impact of spatial resolution of climate data on the potential deployment of renewable generators. Our study finds that for offshore/marine renewables, existing datasets used significantly under-estimate the power production, thus reducing the deployment potential.

Furthermore, this work also looks into the impacts of European grid with marine energies, and quantifies the dispatch generation benefits that marine energies offer. It looks into the 100% renewable scenario for all countries in the European Union and the United Kingdom via the inter-connector. The study quantifies the added value of marine renewables both in generation and area coverage.

The study assesses and discusses the impacts of coarse and high resolution climate wave data in the estimates. Our approach concludes by also considering the impact of different mixes in the spatial distribution and implications on EU grid by incorporation of marine renewables,

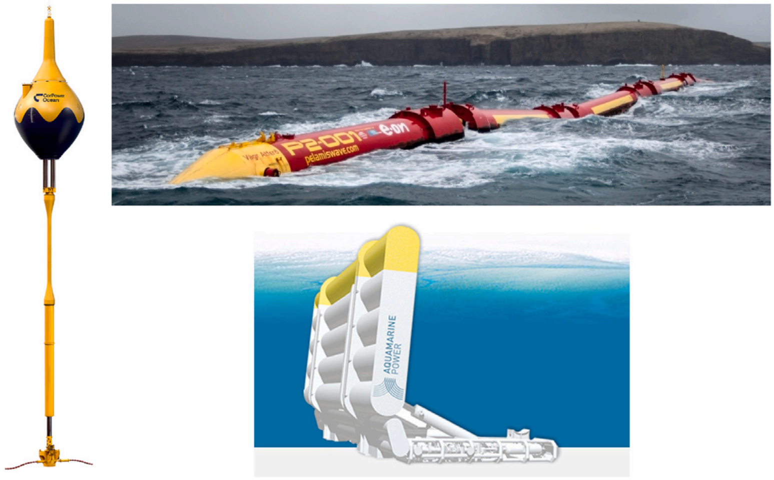


Fig. 1. The WECs used within this study are (a) PA inspired by C4 Corpower (left), (b) Pelamis (right top), and (c) Flat-type (right bottom).

especially of wave energy and floating wind that are often underutilised. Results show that marine renewables, if properly incorporated, can offer significant advantages, reduce energy storage dependencies, energy costs, and enhance energy independence.

Finally, we consider also the European Commission's published targets and economic considerations for marine renewables, and uncover the distribution of generators, revealing that wave energy and floating wind are applicable in modern energy systems.

Our approach builds upon open source modelling, and significant extension of the PyPSA-Eur model. Our new version with marine renewables, has been developed by the Marine Renewable Energies Lab (MREL, www.tudelft.nl/ceg/mrel) at Delft University of Technology, henceforth known as PyPSA-Eur-MREL.

2. Materials & methods

PyPSA-Eur is an optimisation model specific for the European power system at the transmission network level modelled on the Power System Analysis (PyPSA) toolbox [13,28], covering the whole European Network of Transmission System Operators for Electricity (ENTSO-e) area. It is suitable for operational studies, generation, and transmission expansion planning studies. For the first time, Wave Energy Converters (WEC), floating solar, tidal energies extension were integrated into PyPSA-Eur, enabling the assessment of the impact of wave energy on the European Energy Grid. In addition, care has been taken to represent floating wind based on the state-of-the-art.

The WECs used take into account different depth zones for deployment, removing biases in the selection and adaptation of the study. Representing the power production of a WEC in PyPSA-Eur-MREL, a proper approach has been used via incorporating a power matrix. For each device, a power matrix has been constructed based on a combination of frequency domain model and integration of weakly non-linear hydrodynamic modelling i.e viscous damping, based optimal PTO coefficient within a computationally efficient framework.

It is often the case that Energy System Models (ESM) want to reduce the amount of complexity of wave energy, by using efficiency coefficients. However, what ends up happening is the generalisation and not proper representation of the operation of WEC in complex seastates, hence the cut-in, cut-off, peak and low power conditions are often mis-characterised leading to skewed results [27,29,30].

The WEC functionality incorporated in PyPSA-Eur is coupled with metocean conditions, providing the capacity factors, and taking into account depth deployments of each raster cell. In our consideration, usable area i.e. how much is the maximum installed wave generation capacity is computed. A packing density of $20 - 50\ \mathrm{MW/km^2}$ was considered feasible by Lavidas et al. 2021a,c [26,31]. The extension for waves has considered for three different devices based on depth of deployment, with packing density for shallow $30\ \mathrm{MW/km^2}$, nearshore $35\ \mathrm{MW/km^2}$ and farshore $50\ \mathrm{MW/km^2}$. The WECs represent the sector's most widely utilised devices. The WECs considered include a point absorber whose geometry is inspired by the Corpower C4 WEC (point absorber-nearshore), Pelamis (attenuator-farshore), and a flap type (terminator-shallow), see Fig. 1. The power matrix for the point absorber was developed within MREL, while the power matrices for other devices were adapted from [32–34].

In order to produce the power matrix for the point absorber device, a weakly non-linear boundary element formulation is used, developed utilising the open-source BEM solver HAMS-MREL [35]. These can resolve the complex hydrodynamic interactions, whilst also accounting for the Power-Take-Off through an optimal passive control strategy considering displacement constraints. The basis for the hydrodynamic model utilised is from the work of Alday et al. [36]. The power matrix is constructed considering irregular sea states based on the JONSWAP spectrum for the power calculation. The WECs represented are noted as shallow (0–20 m depth), nearshore (20–80 m depth), farshore (50–150 m depth), see Fig. 2. The wave power production for each WEC is provided by the power matrix (PM) and according to Eq. (1).

$$E_o = P(H_{m0_{i,j}} \cap T_{i,j} \cap Pk_{dir_{i,j}}) \cdot PM_{i,j} \cdot \Delta T \qquad (1)$$

where ΔT is time, significant wave height (H_{m0}), T can be any wave period used by a WEC such peak wave T_{peak}/ energy period T_{m10}, mean zero crossing/T_{m02}, peak wave direction (Pk_{dir}) (if available in the power matrix), for different latitude and longitude locations (i,j). These variables allow for the characterisation of a given sea state, and in combination with a WEC power matrix (with and without directional information) are used to estimate the power output of a device [27].

PyPSA-Eur-MREL also includes the considerations for floating wind, based on the NREL 15MW as its reference turbine [37] as shown in Fig. 3. Wind energy is estimated based on the existing process in PyPSA-Eur, however, depths and distance from shore have been factored in for floating wind. For WECs, depth and distance from shore factors have also been added, but also an applicability factor to represent where they are expected to be deployed.

Whilst working on the wave energy integration, we encountered that the use of coarser re-analysis datasets is widespread. However, there are significant drawbacks that need to be considered here. Probably most obvious limitation, is the spatial resolution of global models, typically ranges from 0.5^o to 0.25^o, which is equivalent to ≈55 km to

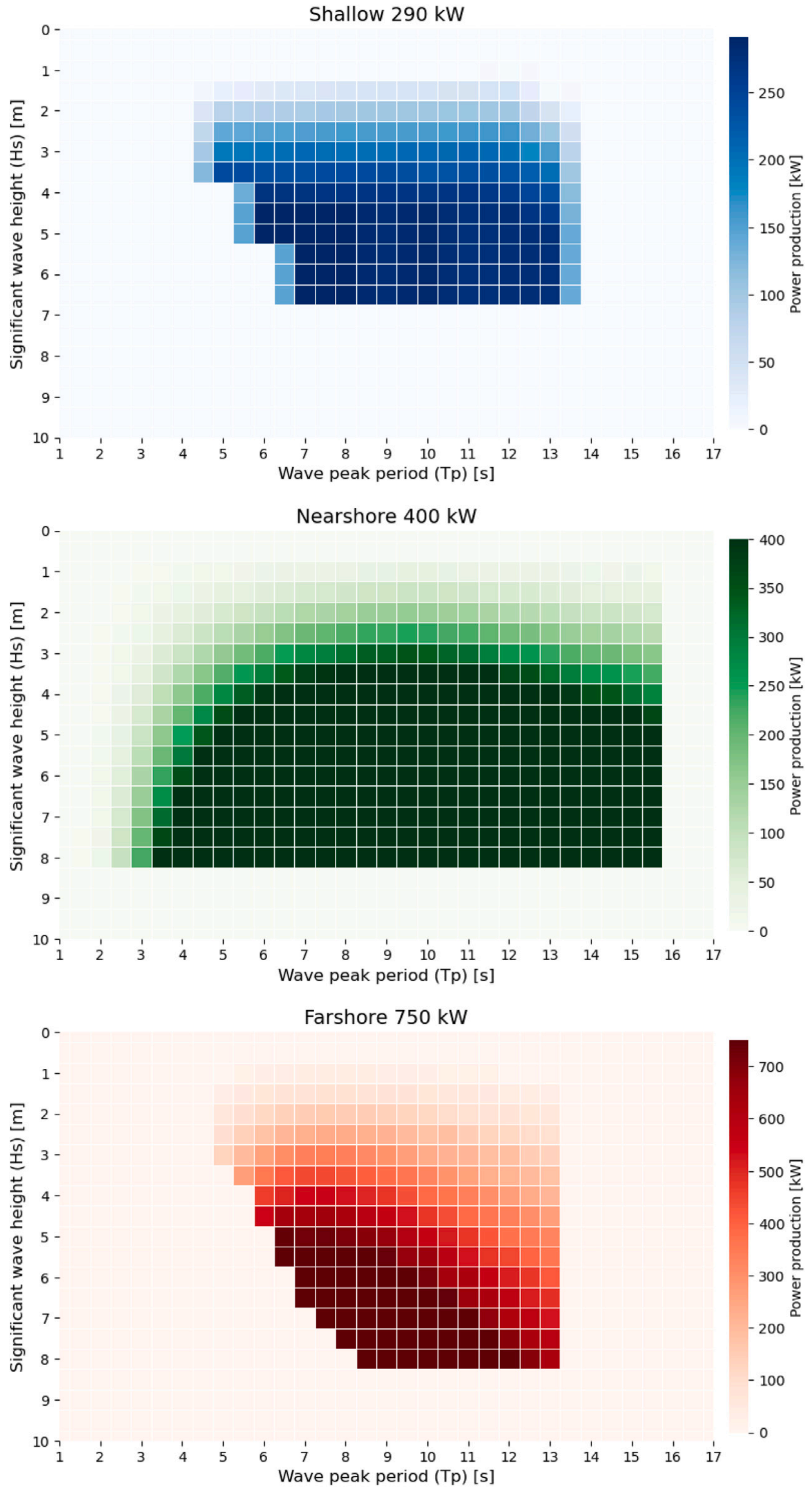


Fig. 2. Power matrices for WECs used in PyPSA-Eur-MREL, shallow is a terminator, nearshore is a point absorber, and farshore is a hinged attenuator.

≈27 km [38,39]. Comparison of ERA5 wave data with along-track satellite data, and the ECHOWAVE dataset, reveals that the performance of ERA5 degrades as the wave heights increase [36,40].

The ECHOWAVE 30-years hindcast provides (∼2.3 km) and temporal (1 h) resolution wave fields and spectral data within the European coastal shelf. One of the main characteristics of this dataset is the use of the TUD-165 parameterisation and wind intensities correction proposed by Alday & Lavidas [40]. The use of TUD-165, together with the selected forcing fields, helped to reduce the overall wave heights' biases in the North-East Atlantic. Adjustments that led to the proposed parameterisation were extensively verified (and then validated) with measurements from the ESA Sea State CCI V3 altimeter product [41]. The resolution and accuracy of ECHOWAVE is an excellent tool for a detail estimation of the energy flux within areas of interest for the development of wave energy projects (typically in depths bellow 200 m).

Fig. 3. The semi submersible floating wind turbine with nominal power of 15 MW [37].

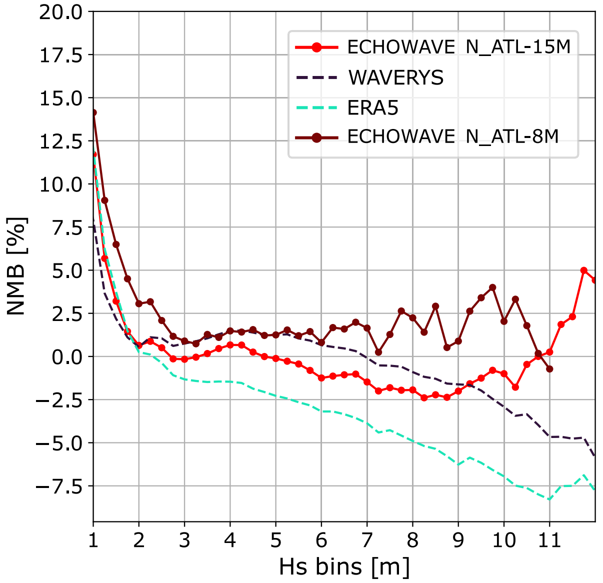


Fig. 4. H_s Normalised mean bias (NMB) between altimeter data from Jason-3, WAVERYS, ERA5 and the ECHOWAVE hindcast. NMB computed using altimeter and model data from 2016 to 2020. N_ATL-15M and N_ATL-8M grids have 0.25° and 0.125° of spatial resolution respectively.
Source: Figure adapted from Alday & Lavidas [40].

Fig. 4 shows the normalised mean bias of H_s from global models ERA5 and WAVERYS [42], and the coarse (N_ATL-15M) and intermediate (N_ATL-8M) resolution grids from ECHOWAVE. The NMB (model-altimeter) was computed for the North-East Atlantic area using 5 years of data (2016 to 2020). ECHOWAVE N_ATL-15M and WAVERYS show a similar performance levels up to H_s of 9 m, ECHOWAVE in general performs better for $H_s > 9$m. Note how bias levels are better constrained, across the analysed wave heights' range, when the wave field is solved with higher spatial resolution (ECHOWAVE N_ATL-8M in Fig. 4). ERA5 shows the largest reduction in accuracy, specially for $H_s > 7$m, with an underestimation of wave heights reaching $\approx -7.5\%$.

Thus, it could be generalised that the closest output from the models' gridded data is about 20 to 30 km offshore. In most cases this corresponds to deep water conditions, where wave propagation is not affected by interactions with the surrounding bathymetry. In some regions where these models compute results for shallower depth conditions (e.g. North Sea), they normally do not properly resolve bathymetric features which can easily be translated to an over or under estimation of wave heights [27,43,44].

Given that the main novelty of PyPSA-Eur-MREL is the inclusion of wave energy, the coarse resolution of ERA5 must be avoided when integrating WECs. Estimating wave energy production with ERA5 leads to significant under-estimations in power production, with recorded under-estimating differences ≈25%–30% [45]. To mitigate this a high fidelity ECHOWAVE European wave energy database of wave conditions is providing the metocean information with spatial resolution 4 km covering all of Europe and United Kingdom.

For tidal resource we added constituents and velocities from the re-analysis of the North-West European Shelf with a 7 km resolution. The ocean model is NEMO (Nucleus for European Modelling of the Ocean), using the 3DVar NEMOVAR system to assimilate observations [46].

The same issue is also prevalent for wind, hence the used dataset used in PyPSA-Eur-MREL is updated with the Copernicus European Regional ReAnalysis (CERRA) [47]. The Copernicus European Regional Reanalysis (CERRA) is a state-of-the-art dataset, as it offers a high-resolution pan-European reanalysis with a 5.5 km horizontal resolution and 106 vertical levels. The dataset is derived from downscaling the global ERA5 reanalysis using the Harmonie NWP system, with ALADIN physics, Operational Interpolation (OI), and 3D-VAR for both surface and upper-air analysis. ERA5 is a re-analysis dataset with a 32 km resolution, that is often insufficient for capturing the detailed wind resource characteristics near coastal waters, crucial for offshore wind energy projects. In contrast, CERRA's 5.5 km resolution enables a much better capture of coastal effects, leading to more precise resource assessments near coastal boundaries. One significant distinction between CERRA and ERA5 also lies in the temporal resolution, ERA5 provides hourly data, CERRA delivers analyses every three hours, spanning from the early 1980s to near real-time. For PyPSA-Eur-MREL a mixture of CERRA backcasting and forecast conditions are used to develop an hourly dataset, more suitable for energy modelling.

From analysis at MREL, we noted that ERA5 cuts off the wind at 25 m/s, whereas the CERRA follows the observations till 30 m/s, see Fig. 5. Furthermore, ERA5 overestimates the probability density function (PDF) for winds speed up to 10 m/s, where the cut-in and optimal ranges of operations are active. That indicates that if scaled to higher vertical layers, ERA5 will move towards non-operative modes which reduces the effectiveness of wind turbines. However, as it is shown on the PDF, that is not the case, with CERRA having a better correlation with the observations, see Fig. 5.

2.1. Scenarios

The PyPSA-Eur-MREL processes are provided with bold highlighted letters showcasing the additional generators, see Fig. 6. To quantify the impacts of climate fidelity in the deployment of marine renewables by the model, care has been taken to have a proper evaluation. Table 1 gives an overview of all cases used in this study. To further improve this evaluation, the GEBCO bathymetry dataset that the model already uses, was updated to its 2023 version (previously it being 2014), which has 15 arc-second interval grid (≈450 m).

Case 1 is considered the base/benchmark, using coarse ERA5 dataset and all cases are run with a greenfield perspective. Similarly, Cases 2-4 represent the impacts from fidelity datasets. Case 5 uses only high fidelity wind-wave data, but is differentiated from Case 4 in terms of minima capacities. It utilises the targets of the European Offshore Energy Strategy (OES) for 2030 for offshore wind and ocean (wave, tidal) energies. Finally, the high-resolution inputs are also used to

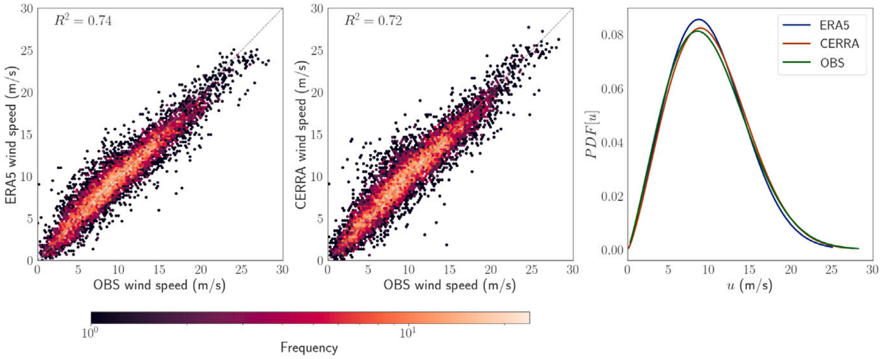


Fig. 5. A comparison of 100 m Wind speeds for ERA5, CERRA and observations (OBS) at the FINO1 station for the year 2011.

Table 1
Datasets used for the different cases for the year 2030 comparing the impacts of all climate data, and dataset used for the impacts of the European Offshore Energy Strategy (OES) for 2030 and 2050.

		ERA5	CERRA	ECHOWAVE
Case 1-2030	wind	✓		
	solar	✓		
	wave	✓		
Case 2-2030	wind		✓	
	solar	✓		
	wave	✓		
Case 3-2030	wind	✓		
	solar	✓		
	wave			✓
Case 4-2030	wind		✓	
	solar	✓		
	wave			✓
Case 5-2030 OES	wind		✓	
	solar	✓		
	wave			✓
Case 6-2050 OES	wind		✓	
	solar	✓		
	wave			✓

provide the 2050 perspective on marine renewables benefits. Both Case 2030-OES (Case 5) and Case-2050 OES (Case 6) give insights into the spatial distribution of marine renewables both for 2030 and 2050, that have never been quantified.

For the United Kingdom, although the Withdrawal of the United Kingdom [48] was provided on the 12th February 2021, the UK is modelled in our approach. This is due to existing and planned connection scheme, as it may be granted access to the system given the latest Memorandum of Understanding (MoU) between the European Commission (EC) and EU [49]. In this study, the grid is modelled by using 130 nodes, with each country required to produce at least 75% of its energy demand, and the ability to exchange electricity via grid lines.

PyPSA-Eur is a cost minimising model, hence the objective is to find the solution that minimises costs across the whole modelled power system. The utilised greenfield approach allows us to investigate the cost and feasibility of a power system. Storage carriers such as hydrogen and batteries are considered with maximum hours of support for 168 and 6, respectively. Since the aim is to look into the future for a 100% renewable energy based grid, no fossil and nuclear stations are considered.

2.2. Marine renewable economics

As the PyPSA-Eur-MREL model was being developed, a very sensitive behaviour was noticed with regards to cost modelling assumptions [50,51]. Given the plethora of options in the 100% renewable energy system, the marine costs sensitivity are highly influential. Therefore, to realistically consider the 2030, and 2050 future horizon, we have adapted all technological costs via learning curves and external cost databases.

Penetration of wave energy under the renewable energy scenario is not only dependent on costs, but also the cost of competing renewables. Wind and solar, have achieved relevant cost reductions over the past decades. For this reason, technological learning, the process under which cost reductions are achieved as a result of production growth, is considered in this study for marine renewables. Technological learning is modelled through the one variable factor-learning curve approach [52,53].

Learning factors that can influence cost reductions are; learning by doing; learning by research; learning by interaction and knowledge diffusion; learning by upscaling manufacturing capabilities; and learning by up-sizing of a product [53]. This approach is utilised to estimate the capital cost of wave energy in the 2030, and 2050 horizons, serving as the cost based scenarios to explore the penetration of WECs. In addition, WEC cost reductions and the forecasted costs are modelled as an exogenous variable and serve as a parameter for PyPSA-Eur-MREL, with learning effect, when first unit cost is unknown. This can be written as:

$$C_{p2} = C_{p1} \cdot (\frac{P_2}{P_1})^b \tag{2}$$

Where C_{p1} is the cost per unit after the cumulative production of P_1 units, C_{p2} is the cost per unit after the cumulative production of P_2, and b is the experience index, which defines the effectiveness with which the learning takes place. The formulation implies that after each doubling of production, the price is multiplied by a factor of b, called the Progress Rate (PR). The learning rate is defined as 1-PR and refers to the reduction fraction after each doubling. A progress ratio (PR) of 90% equals a learning rate of 10%, and thus means that unit production cost would decline by 10% and reach 90% of its original value whenever the production doubles [53].

A learning curve visualises the costs decrease by a constant fraction with each doubling of the total number of units. Given the lack of information for “real” learning rates for most marine renewables (floating solar, wave energy, tidal energy, floating wind), a variable learning rate was used to estimate the potential cost reductions more realistically, with a learning rates of 15% used between 2020 and 2030, 10% between 2030 to 2040, and 5% between 2040 and 2050, see Fig. 7. A similar hybrid approach, supported by data and estimates, has been used noted in Coles et al. [54] and used also in other studies [52,55]. In our approach the reduced effectiveness of the learning rate is to represent the mature renewable energy environment where a technology is placed.

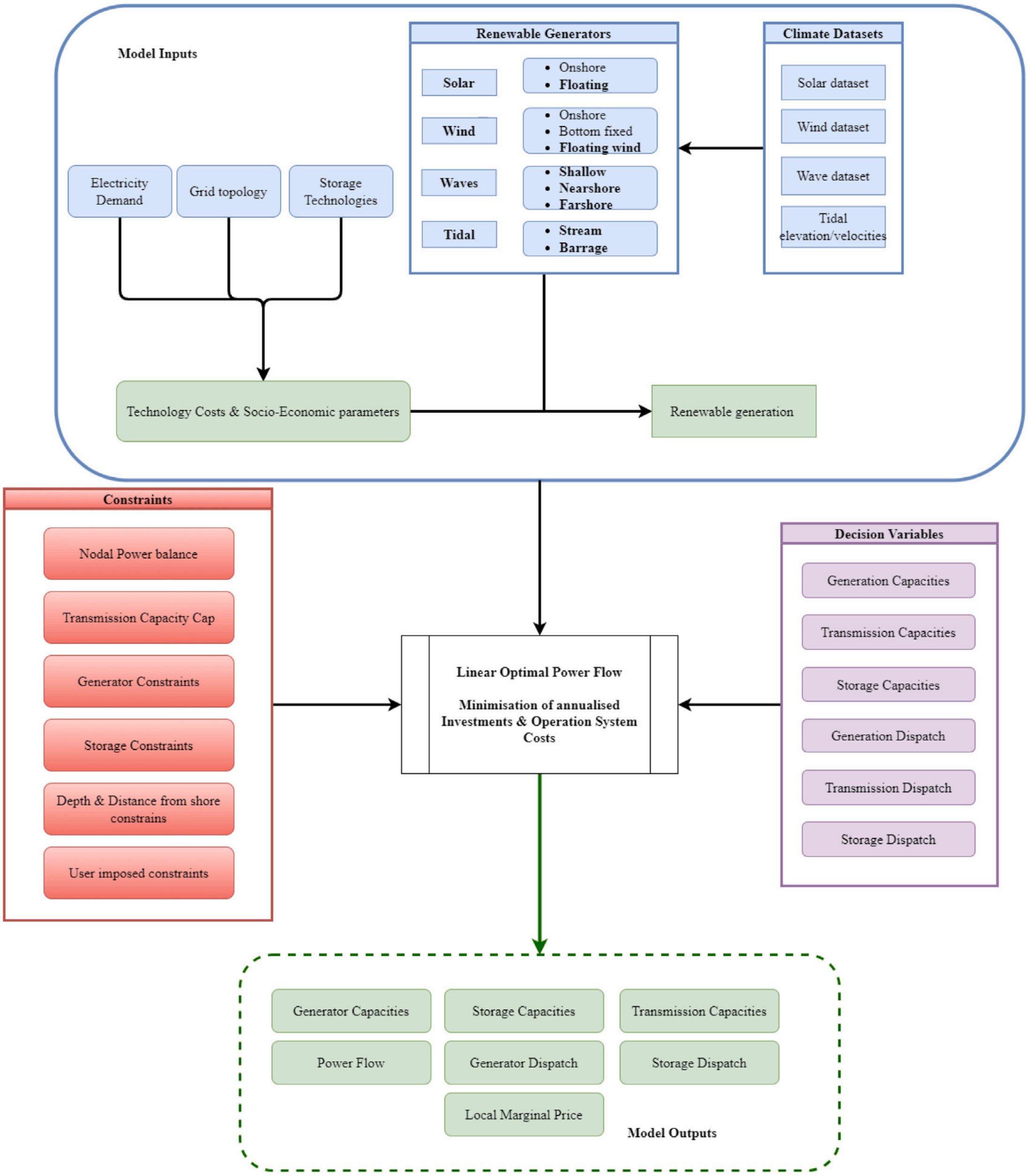


Fig. 6. The process that PyPSA-Eur-MREL uses with added functionalities in marine renewables.

3. Results

3.1. Cost reduction pathways

All technologies LR are modelled with ultimate goals the EU and UK targets for them. For the cases of ocean renewables (wave, tidal), a combination of resulting expected capacities has been set as a 2050 limit. Similarly, for floating wind and tidal, upper limits have been set. For floating solar no such limit is introduced, as no official targets have been set. Nonetheless, the annual growth rates are set equivalently with all other marine renewable technologies.

For wave and tidal energy, there is a combined target of 40 GW by the European Commission (EC) [56] and 22 GW by the UK [57]. Whilst the future is unknown, past experiences have shown that deployment goals are not easy. This study considers that out of the total 40 GW in the EU, majority will be from wave energy, whilst in the UK 12 GW will be from wave energy and 10 GW from tidal barrages and stream.

In PyPSA-Eur-MREL, wave technologies are represented by three types, so within the capacity targets, the technologies are separated, but not equally. By 2021 the real wave installed capacities had a distribution of 25% farshore, 50% nearshore and 25% shallow. Therefore the same discretisation is used for the 2030, 2040, 2050 goals for wave energy. For tidal barrage and tidal stream are represented equally as 50% of the final target. In total, by 2050, wave energy converters are anticipated to have a total capacity of 52 GW (farshore 13 GW, nearshore 26 GW, shallow 13 GW).

For estimation of WEC initial costs a variable rate per type has been considered, with the farshore device has a cost of 5 million €/MW, nearshore 4 million €/MW, and shallow 3 million €/MW [26,50,52, 58–63]. The reduction pathways for each device can be seen in Fig. 7, where in 2050, even with a conservative adjustable LR, all devices can reduce their CAPEX to $\approx 890 - 1500$ €/kW. The fixed Operational Expenditure (OPEX) of the WECs are a function of CAPEX with farshore 10%, nearshore and shallow being 5%.

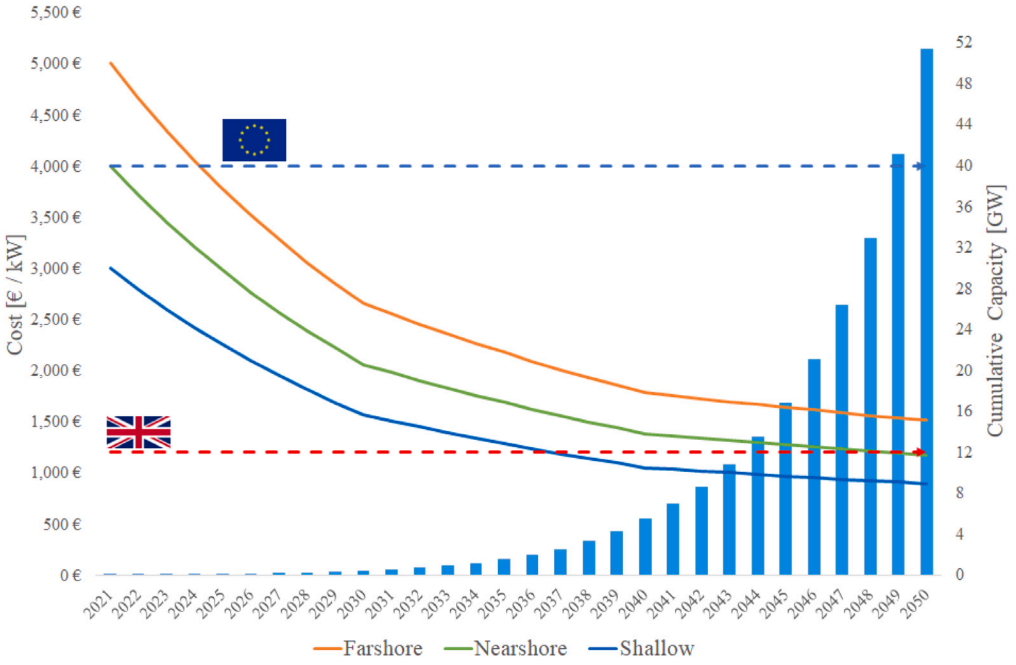


Fig. 7. Application of the variable learning rate for WEC deployments, the three different devices (farshore, nearshore, shallow) are modelled. The first *y*-axis shows the CAPEX per WEC, and the second *y*-axis the deployments needed to achieve the country targets, the lines red and blue point to the installed capacity targets of UK and EU.

Tidal energy is separated into two technologies, tidal stream using the velocities of local waters, and tidal barrage using the difference in elevation. While, tidal technology is considered emerging, tidal barrages have been used since the 1960s. The most famous and oldest is the La Rance tidal station in France. It was constructed in 1966 with a capacity of 240 MW with a cost (adjusted to current prices) ≈847 million Euro [64]. Most recent commercial tidal energy converter is the Meygen project by SAE, which has its Phase 1 operation (6 MW installed), with Phase 2-3 awarded Contract for Difference (CFD) with expected total additional added capacity of 50 MW and future bid plans to install 342 MW [65]. The CAPEX cost for the first round of the Meygen Project was reported at ≈8.1 million £(≈9.2 million €) [54].

In the case of floating wind as starting cost assumptions, the Hy-Wind and the Wind Float Atlantic were considered. Hywind is the world's first floating offshore wind farm. Located off the coast of Aberdeenshire. The project received funding, as first of its kind costing 210 million £(≈240 million €), with an installed capacity of 30 MW [66]. Wind Float Atlantic (WFA) is a pre-commercial project that represents an investment of about 120 million €, located off the coast of Viana do Castelo, Portugal, with installed capacity 25 MW (3 wind turbines rated at 8.4 MW).

For offshore wind in 2050 it is expected that the minima capacities are at least 300 GW for the EU, and 122 GW for the UK, representing both bottom fixed and floating wind. Therefore a clear need exist to separate the two in our study, to enhance insights. Bottom fixed wind currently in PyPSA-Eur has a maximum depth of deployment of 60 m which we kept. For floating wind in PyPSA-Eur-MREL a deployment depth was set from 60-150 m till 2040 and 250 m by 2050. Therefore, it is expected that the majority of installations will move towards floating wind as it also has reduced visual impacts, especially when considering GW scale farms. For EC, it is considered that 200 GW of floating wind is feasible, as most EU Seas and Member States have sharp depth variations (i.e. Mediterranean [67]), and for the UK 60 GW. For both, the total expected floating wind only installations are expected to be 420 GW, with an initial capital expenditure of 6.5 million €/MW, see Fig. 8.

For deployment rates as well as learning rates, the findings of Wiser et al. [68] have been taken into account, that showed that actual cost reduction used in energy models, were too pessimistic. In fact, their study showed CAPEX reductions were almost 50% higher than anticipated. The price per kW we find, is close to the EU reference scenario with 2050 cost per kW only having a difference of 25€/kW in the CAPEX. The fixed Operational Expenditure (OPEX) of floating wind is a function of CAPEX 12%.

Finally, for floating solar, a technology that is experiencing rapid development, we have considered the total installation costs at 10 million €/MW , presented in Martinez et al. [69]. The work is comprehensive, as it not only presents the potential, but also quantifies the impacts of the wave resource and moorings across the Atlantic and Baltic European coastlines, with lowest value CAPEX ≈6 million €/MW and highest ≥16 million €/MW, depending on the depth, distance from shore and exposed wave conditions. The fixed Operational Expenditure (OPEX) of floating solar is a function of CAPEX 12%.

Further economic considerations for PyPSA-Eur-MREL to all other technologies have been modified according to the European Union Reference Scenario 2020, for all relevant technologies, see Fig. 9. All the economic considerations have been revised according to input provided by Joint Research Centre and the European Union Reference Scenario [62,70].

3.2. *Foresight potential for 2030*

Cases 1-5 are focused short term to 2030, with first "benchmark" Case 1, driven only by the very coarse ERA5 data, and Case 6 gives a 2050 viewpoint. The built energy system showcases that mostly onshore renewables are chosen, with a clear dominance of onshore wind, see Fig. 10(a).

Most Northern countries have predominately onshore and bottom fixed wind, with total installed capacity ≈1.45 TW. At the European South Central regions, solar Horizontal Single Axis Tracker (HSAT) are also part of the energy mix, with total capacity ≈371 GW. Hydropower and Pumped Hydro dominate the installations in the European North (Norway, Sweden, Finland). From marine renewables, floating solar and wind, do not show any installed capacities, however, bottom fixed (offshore wind) make up ≈87 GW (see Fig. 10(b)). Also for the first

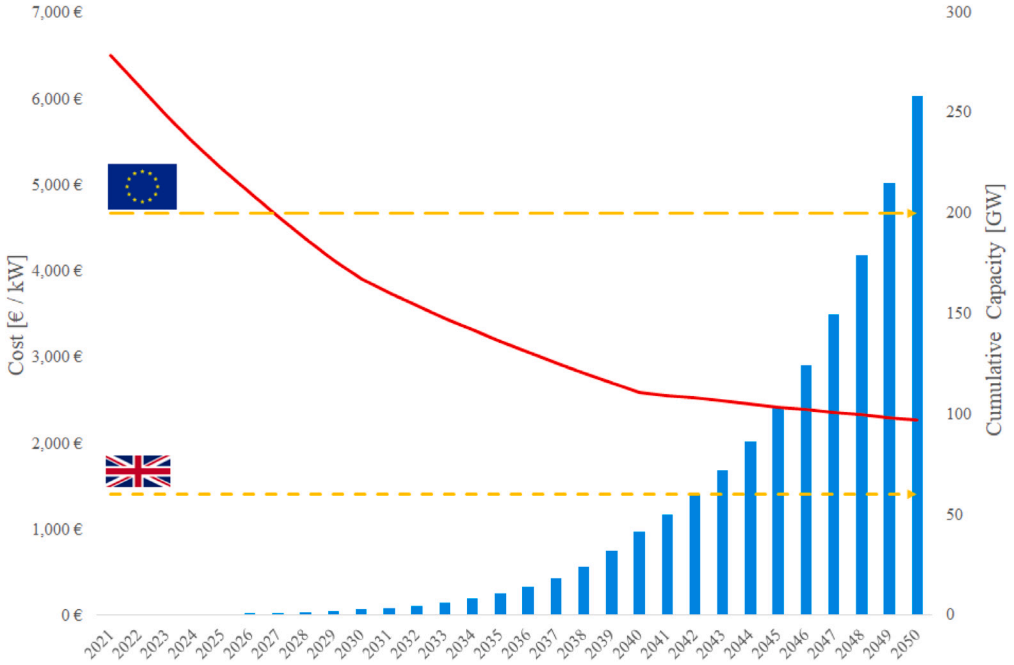


Fig. 8. Application of the variable learning rate for floating wind deployments The first y-axis shows the CAPEX per floating wind, and the second y-axis the deployments needed to achieve the 300 GW target, the orange lines indicate the targets installed capacities.

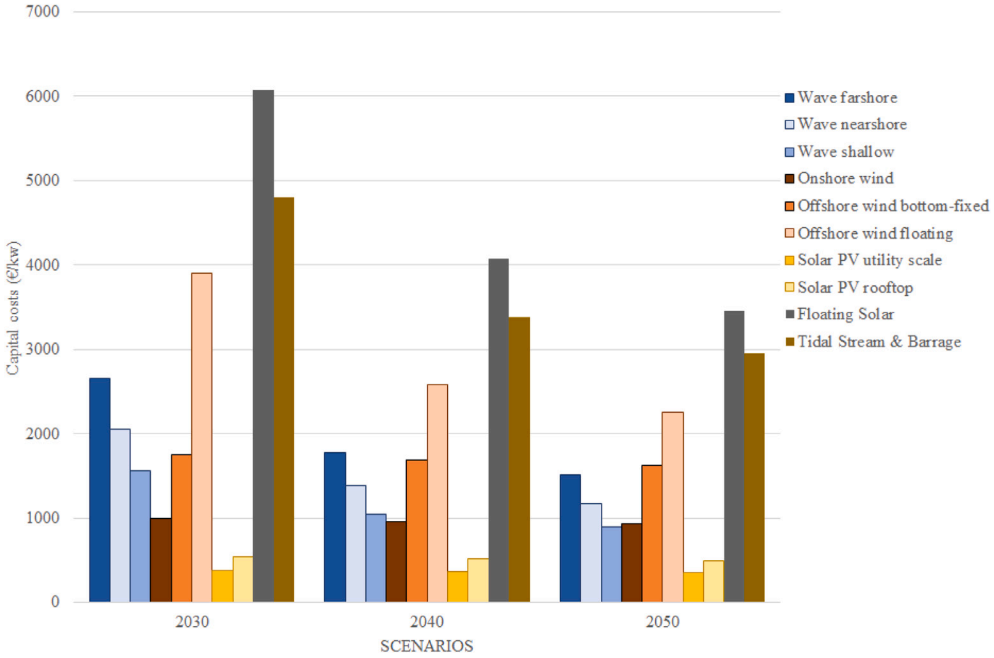
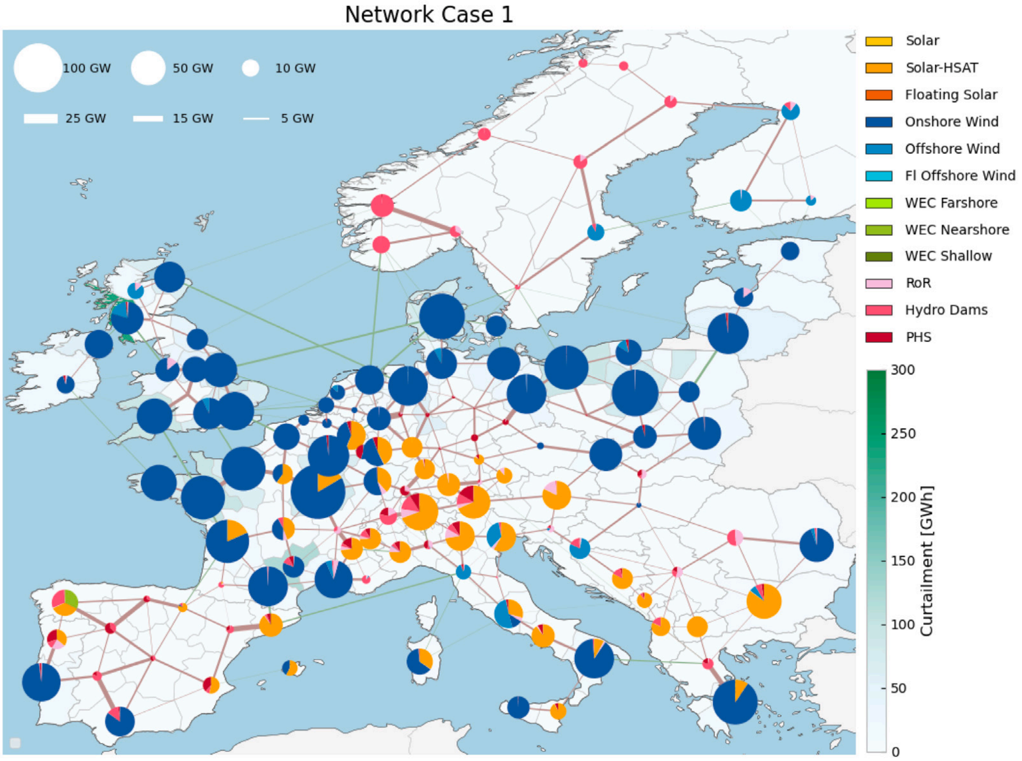


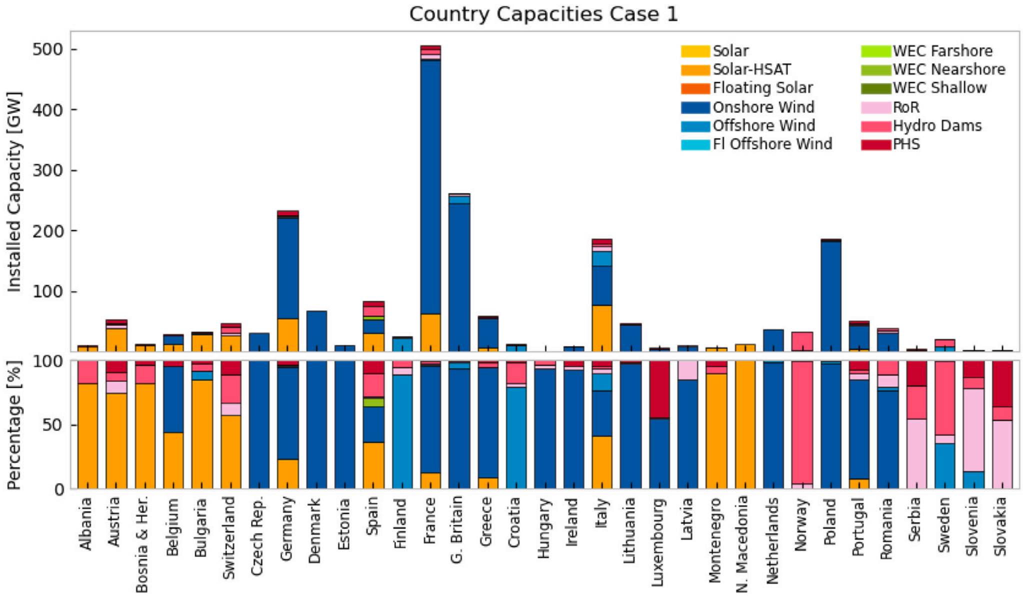
Fig. 9. The variable scenarios and associated cost per technology used in this analysis. The values have been derived after analysis of the EU reference scenario and analysis conducted by the authors.

time, wave energy is also considered with 6 GW installed in Spain, utilising the nearshore WEC, see Fig. 10(b). For Case 1, energy storage also has a high installation rate, hydrogen (H_2) storage has a 93 GW installed capacity, and production of 37 TWh. Battery storage installed is 92 GW and provides ≈104 TWh.

In Case 2 (ERA5-CERRA) wind onshore again is a dominant power source (see Fig. 11(a)). In Northern countries onshore wind is used predominately, but with lower capacities installed. One element to highlight by using CERRA, wind resources are better represented in operational conditions. In Case 1 onshore wind produced 2206 TWh with curtailment recorded to be 1679 TWh. For Case 2 the supply is the about the same 2603 TWh, with a much smaller installed capacity (≈705 GW) of less than half, and curtailments reduced to 1045 TWh, making the use of onshore wind more efficient with less losses. This lead to the capacity factor increased, but on a temporal basis the curtailment reduced. This is reflected also in the smaller capacities that solar achieves ≈70 GW, when compared to Case 1 of 371 GW. In this scenario, marine energies are not utilised due to higher costs. Interestingly, the high utilisation of wind resources results in not including the installation of H_2 storage, batteries install 60 GW with a production of 34 TWh. The higher resolution wind data allows the demand to totally be satisfied without the need for excessive storage.



(a) Network distribution



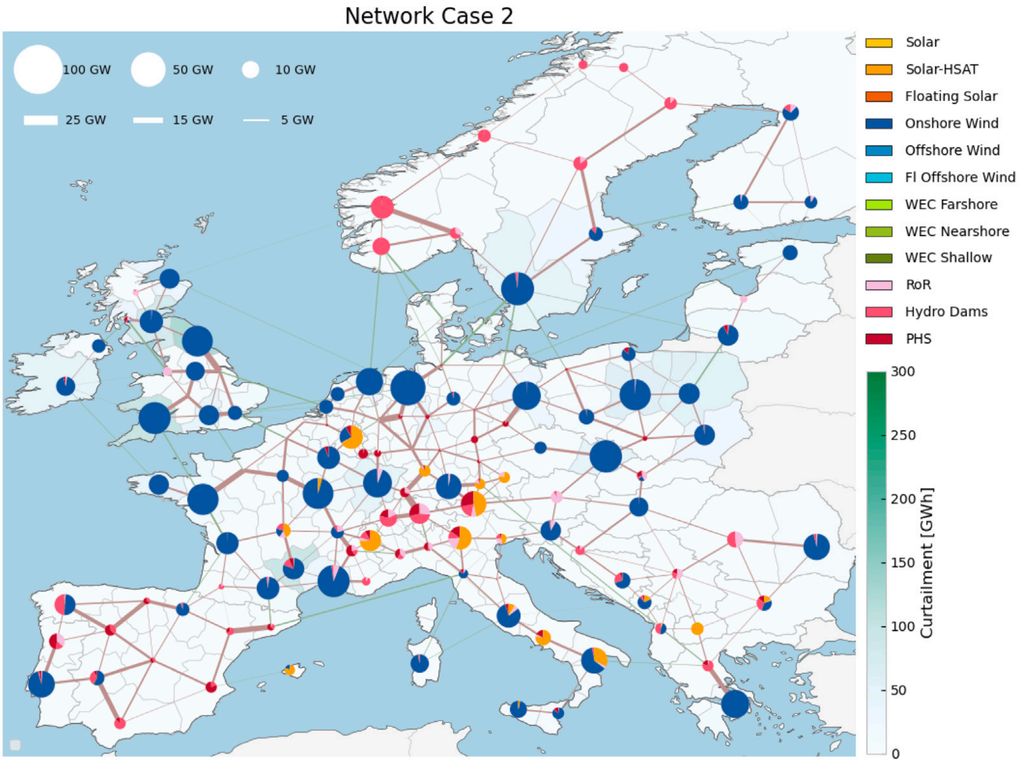
(b) Capacities per country

Fig. 10. Installed generators for Case 1 (a) spatial network distribution with visible expansion lines, it also includes the countries/regions where the majority of aggregate curtailments appear (b) Installed capacity and percentage for each generator category per country.

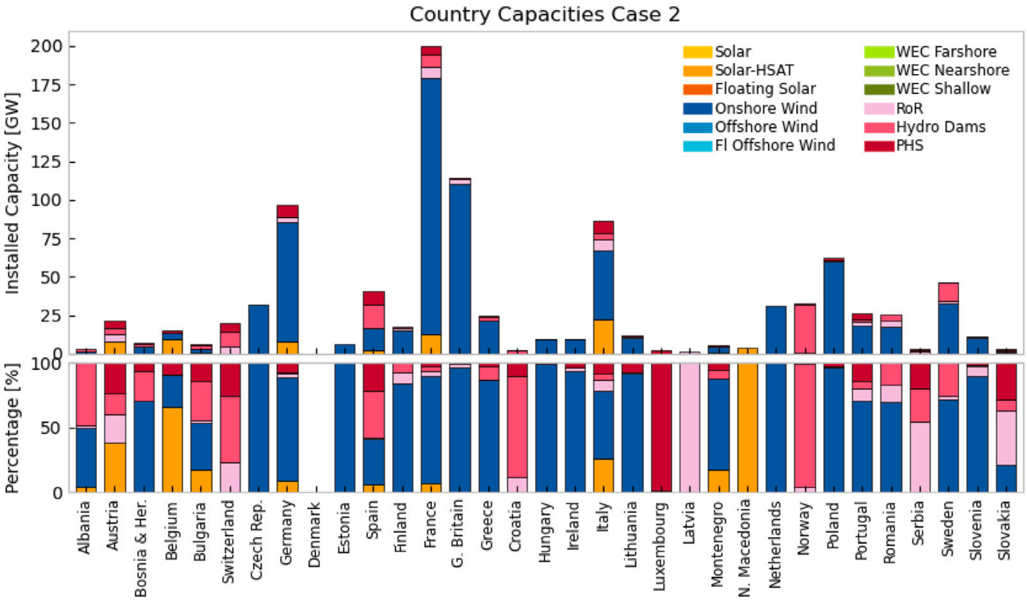
Case 3 (ERA5-ECHOWAVE) uses a high resolution dataset for waves and this has also an immediate unique effect. Due to better wave representation, wave installations achieve 22 GW of total capacity, well above the 1 GW targets of the 2030 EC. These are located predominately in Ireland (10 GW) and Spain (12 GW). This shows the ability when using higher fidelity dataset, to take advantage of resource production potentials, that otherwise could not be considered. Spain shows to have the most diversified profile in terms of generation, followed by Italy, see Fig. 12(a).

In Case 3 due to the lack of good climate information for wind, more energy storage is needed, as wind is considered as a main “base” load generator. Therefore, installed capacities of H_2 of 94 GW are almost identical with Case 1. In terms of battery storage also similar capacity is recorded with 91 GW.

Case 4 (ERA5-CERRA-ECHOWAVE) is highly similar to Case 2, that uses only high resolution wind data. In this instance, the high wind energy potential, combined with high efficiency of wind and low onshore costs, has lead to the system looking very similar to Case 2.



(a) Network distribution

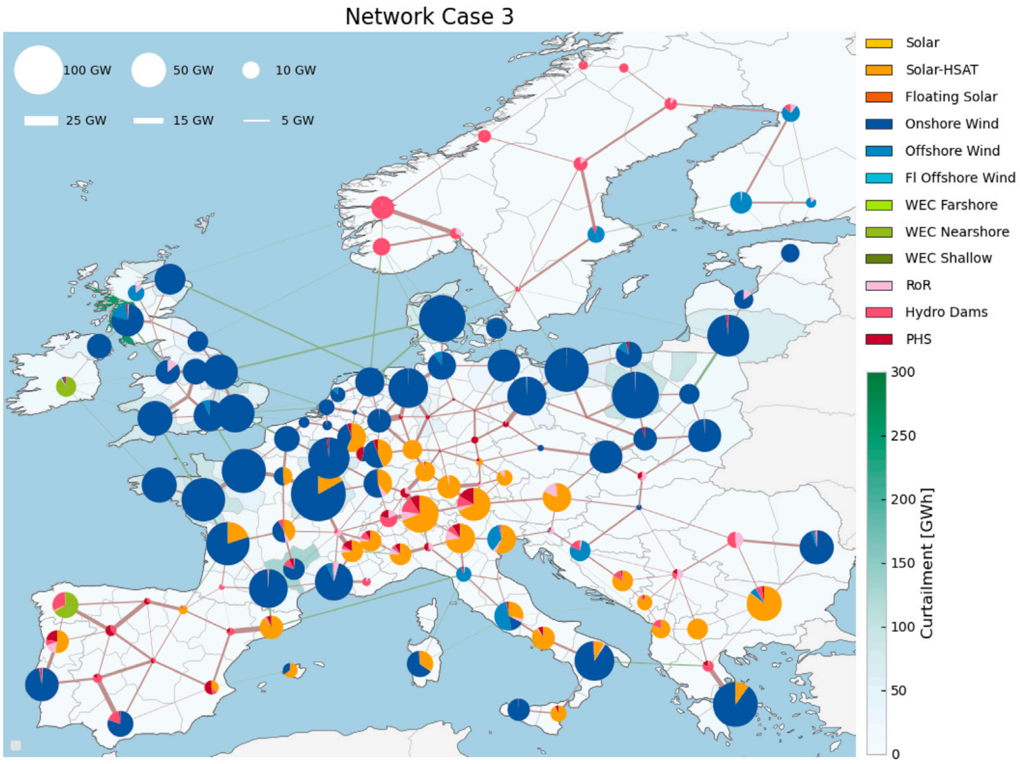


(b) Capacities per country

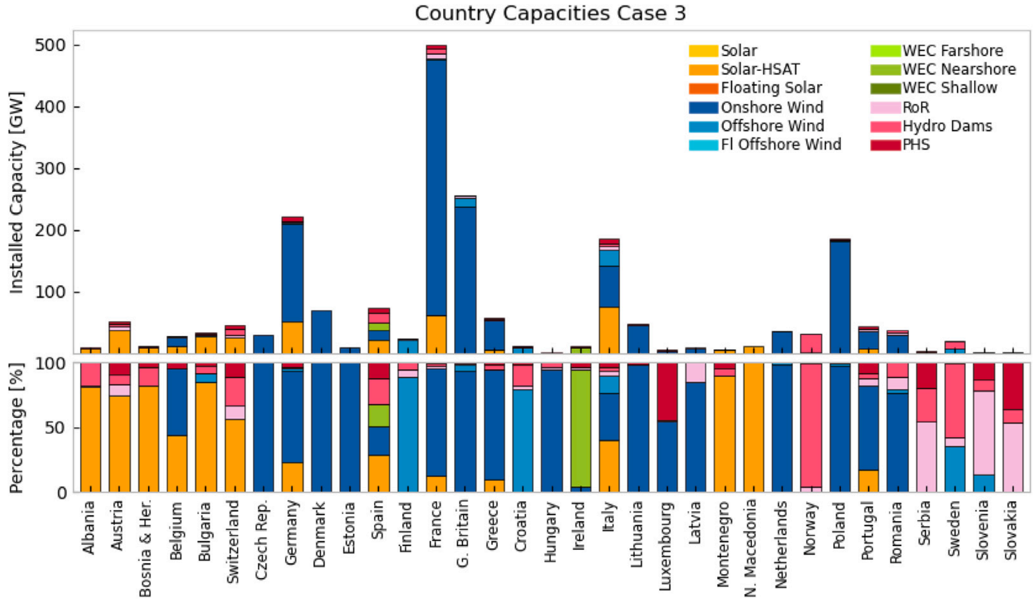
Fig. 11. Installed generators for Case 2 (a) spatial network distribution with visible expansion lines, it also includes the countries/regions where the majority of aggregate curtailments appear (b) Installed capacity and percentage for each generator category per country.

Onshore wind installed capacities reaches 705 GW, with curtailments being reduced by 50% when compared with Case 1. Case 4 also noted high efficiency in power production reflected in zero H_2 installations, whilst battery capacity reached 60 GW. Concluding this case solar HSAT are the only other type of generator installed, which due to its low costs also sees a capacity of ≈70 GW. Due to the higher costs of marine renewable converters, wave, tidal, floating wind and floating solar experience negligible installation, not affecting the results.

Case 5 (ERA5-CERRA-ECHOWAVE) takes into account expected installed minima capacities based on the OES, see Fig. 13(a). For marine renewables expected installed capacities for bottom fixed wind are 64 GW, floating wind at 46 GW, WECs at 6 GW combined. Offshore wind this time sees more installations, but interestingly this also reduced the curtailment levels by all wind installation even further (both onshore and offshore). Solar HSAT is preferred again throughout, and floating solar sees marginal installations. WECs are installed cumulatively at



(a) Network distribution



(b) Capacities per country

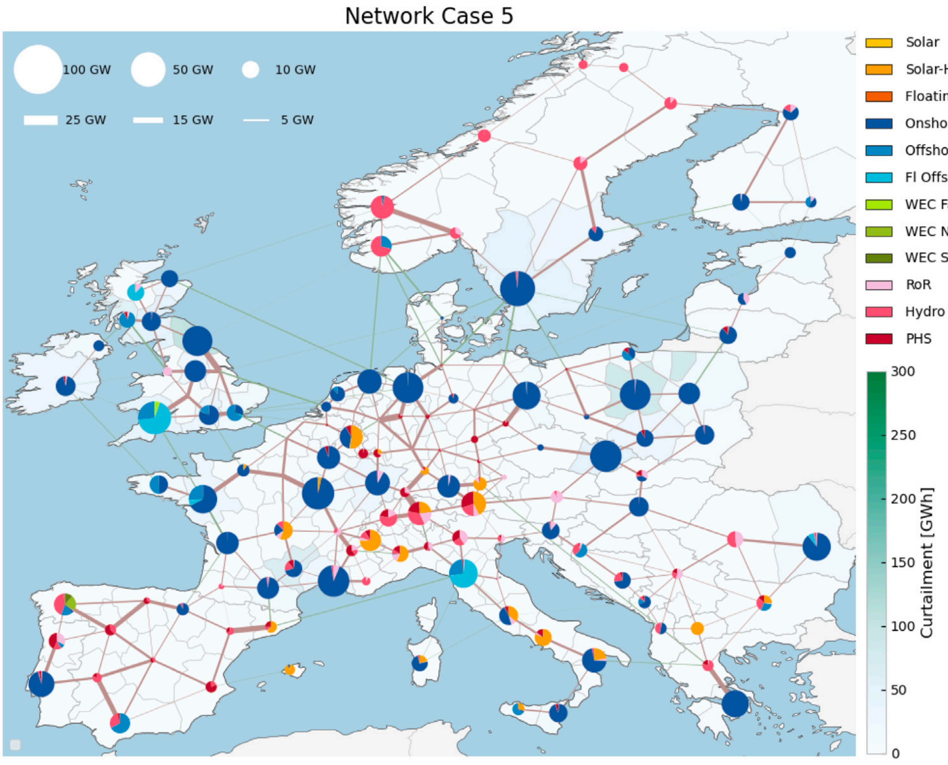
Fig. 12. Installed generators for Case 3 (a) spatial network distribution with visible expansion lines, it also includes the countries/regions where the majority of aggregate curtailments appear (b) Installed capacity and percentage for each generator category per country.

6 GW, the WEC shallow has most of its production curtailed, due to its resource related mostly with locally wind generated waves. WEC nearshore and farshore see the least curtailments with ≈2 GWh each, whilst the production is at 12 TWh and 3 TWh, respectively (see Fig. 13(b)).

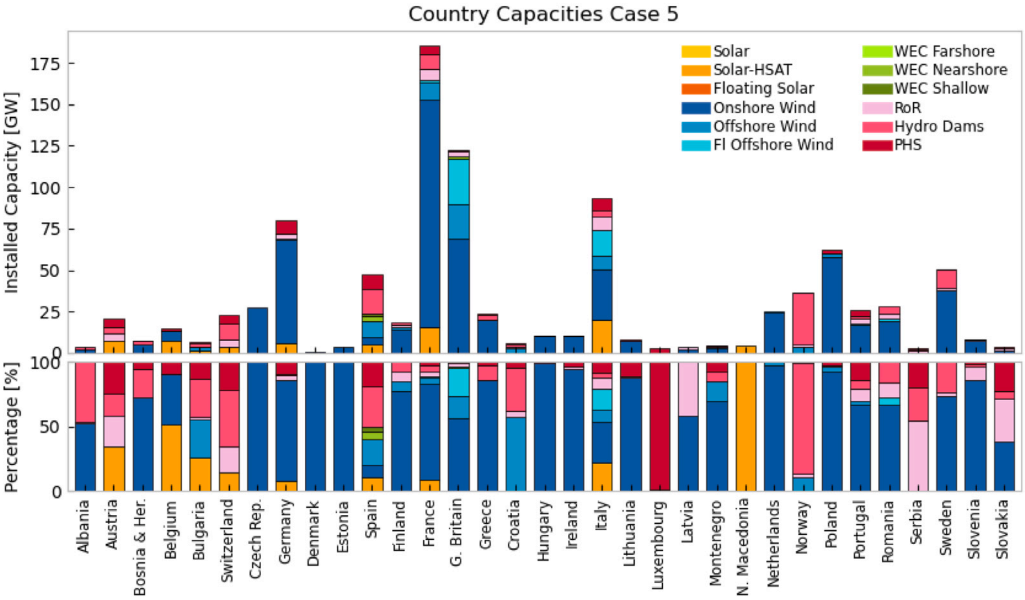
In terms of curtailments, highest losses of produced electricity are seen in regions/countries with mono generators (single type) production (see Fig. 13(b)), such examples are the South East Scotland (UK) which shows dominance of onshore wind surrounding regions. In continental Europe the highest curtailments, for the same reasons, are observed in Central Poland, Sweden and South of France.

3.3. A viewpoint for 2050

Results for 2050, including cost reductions, show us that marine renewables can contribute and are spatially more diverse. Thus, it is worth exploring a first of a kind overview of what the distribution of marine renewables will be in 2050. Following the set up of OES



(a) Network distribution



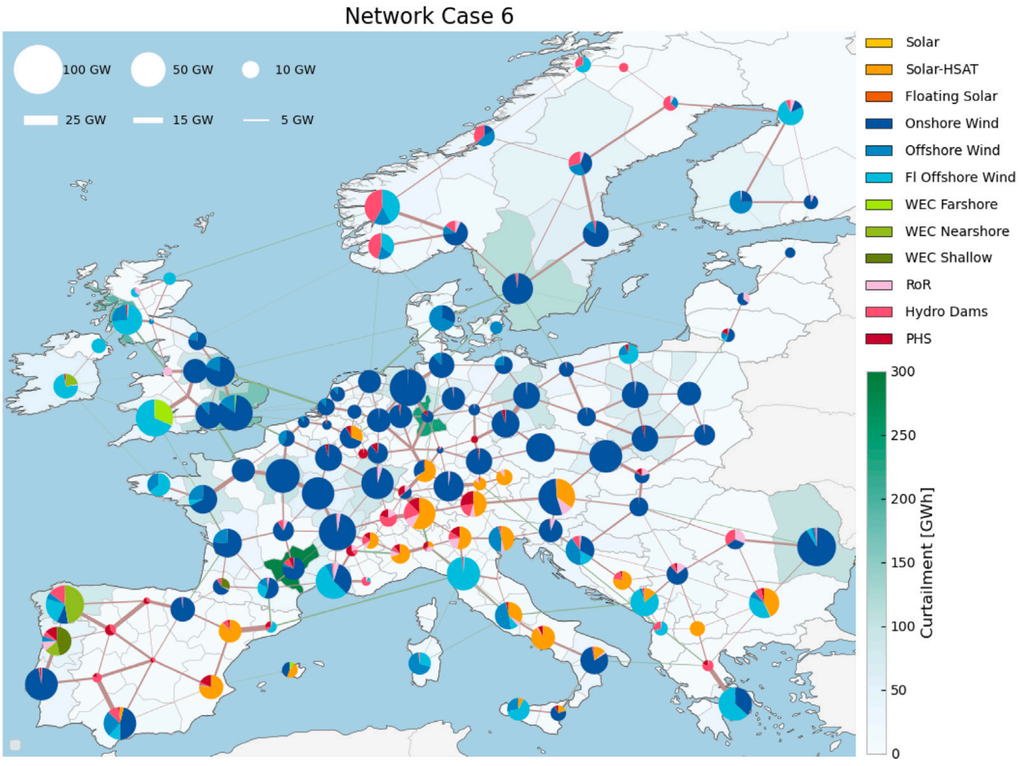
(b) Capacities per country

Fig. 13. Installed generators for Case 5 (a) spatial network distribution with visible expansion lines, it also includes the countries/regions where the majority of aggregate curtailments appear (b) Installed capacity and percentage for each generator category per country.

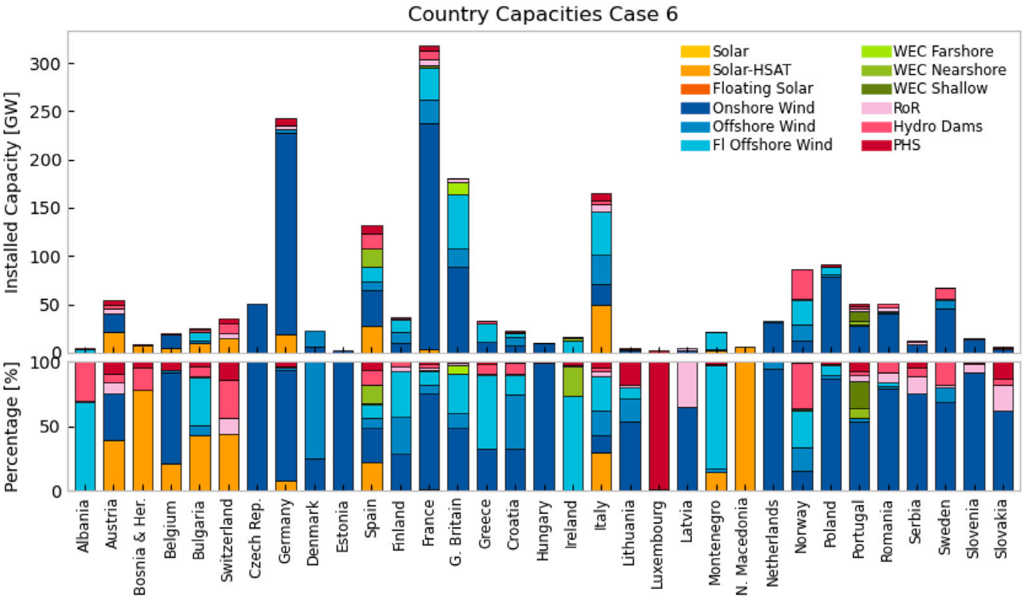
(see Table 1), the 2050 forecast has considered that the electricity consumption will be increased 40% when compared to 2020 [71]. For 2050 (EU and UK) marine renewables, floating and offshore bottom fixed wind are expected to have 420 GW, wave energy 52 GW, and tidal 10 GW, this scenario is called Case 6-2050 OES.

The network distribution (see Fig. 14(a)), shows an even more diverse distribution of the future grid. Floating wind seems to be installed in more coastal region in the Mediterranean. In Italy, specifically within the time-horizon from 2030 to 2050 the floating wind installations increase by 178%, from ≈15.8 GW to 44 GW. Floating wind is also installed in Greece (19 GW), Albania (3.7 GW), Croatia (3.3 GW), France (33 GW), Poland (7.6 GW), Bulgaria (9.4 GW), Finland (13 GW), and Romania (1.6 GW). In Ireland, floating wind totally displaces onshore wind and together with WECs satisfy demand, with 12 GW and 3.65 GW respectively. The United Kingdom (UK) (Great Britain) also sees 55 GW of floating wind and 12.3 GW of WECs.

In terms of curtailments, the change in network distribution has also changed the dynamics, see Fig. 14(a). Most diverse country is Spain,



(a) Network distribution



(b) Capacities per country

Fig. 14. Installed generators for Case 6 (a) spatial network distribution with visible expansion lines, it also includes the countries/regions where the majority of aggregate curtailments appear (b) Installed capacity and percentage for each generator category per country.

and it does also appear to have curtailments of ≈40 GWh. UK exhibits a shift in its curtailments, with the buses at the South East of the country having the largest values. Table 2 gives an overview of all installed capacities for all Cases.

3.4. Implications of marine renewables on energy systems

The higher resolution of wave and wind data shows clearly that marine renewable have a large role to play. In terms of economics the system, the annual system cost of the model driven by ERA5 (Case 1 coarse data throughout) is at 295 billion €/year, in the case of only high-resolution wind data for exactly the same set-up the cost drop to 100 billion €/year. The addition of marine renewables in Case 5 (floating wind, wave energy, solar and tidal), slightly increases the costs to 156 billion €/year, in 2030 terms.

In terms of required capital (Capital Expenditure, one-off) to built a system with 100% for 2030, the higher fidelity data models lead to reduction. In Case 1 the cost of the whole network (generators,

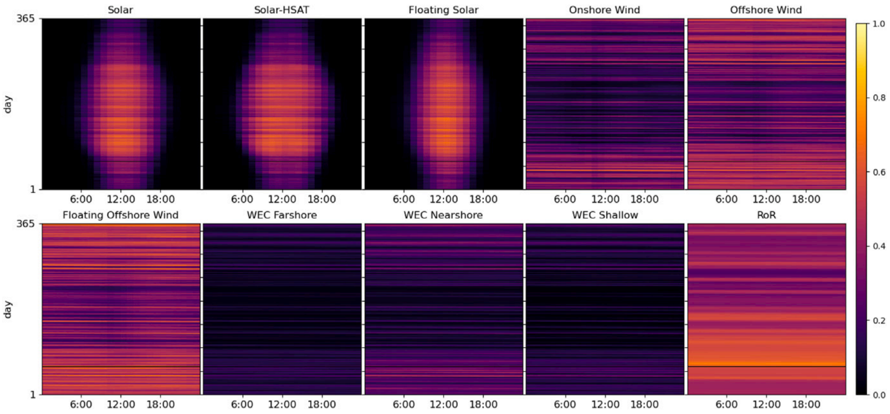


Fig. 15. Availability of resource potentials in Case 1 (coarse data).

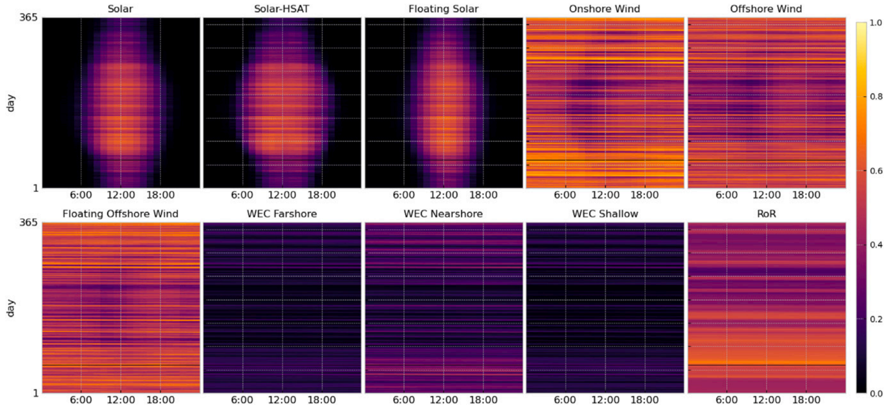


Fig. 16. Availability of resource potentials in Case 5 (high resolution wind and wave).

Table 2
Installed capacities per generators and storage mediums for all Cases.

	Installed Capacity (GW)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Floating Wind	–	–	–	–	46	260
Floating Solar	–	–	–	–	–	–
Offshore Wind	88	–	88	–	64	160
Onshore Wind	1441	705	1 400	705	579	991
Solar	0	0	0	0	0	0
Solar-HSAT	371	69	362	69	71	169
Wave Farshore	–	–	–	–	2	13
Wave Nearshore	6	–	22	–	3	26
Wave Shallow	–	–	–	–	2	13
H_2 electrolysis	25	–	24	–	–	–
H_2 fuel cell	93	0	94	0	0	0
Batteries	92	60	91	60	50	187

Table 3
Installable capacities per Case, and corresponding installable areas required.

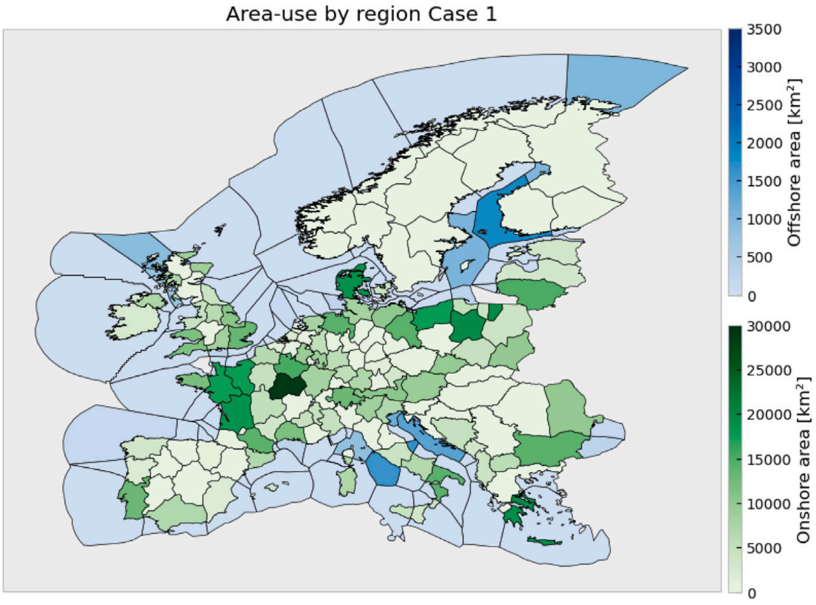
	Total onshore	Total offshore
Case 1	1812 GW 665,892 Km^2	94 GW 171 Km^2
Case 2	774 GW 269,734 Km^2	– –
Case 3	1761 GW 647,390 Km^2	109 Km^2 13,148 Km^2
Case 4	775 GW 269,736 Km^2	– –
Case 5	650 GW 228,366 Km^2	116 GW 14,419 Km^2
Case 6	1160 GW 414,876 Km^2	472 GW 53,182 Km^2

storage, cabling) is at 267 billion €. Case 2 and 4 have higher wind utilisation, and hence the system cost are 102 billion €. Case 3, uses only high resolution wave information, and due to the fact that the system depends still a lot on deploying over-capacity the costs are only 1 billion €cheaper (265 billion €) than Case 1. For Case 5 the energy system has a cost 40% less than case 1, with 160 billion €. These marine technologies, have not benefited fully yet by economies of scale, and even in their early adoption can lead to a reliable system that is almost 40% cheaper that the coarse oriented solution.

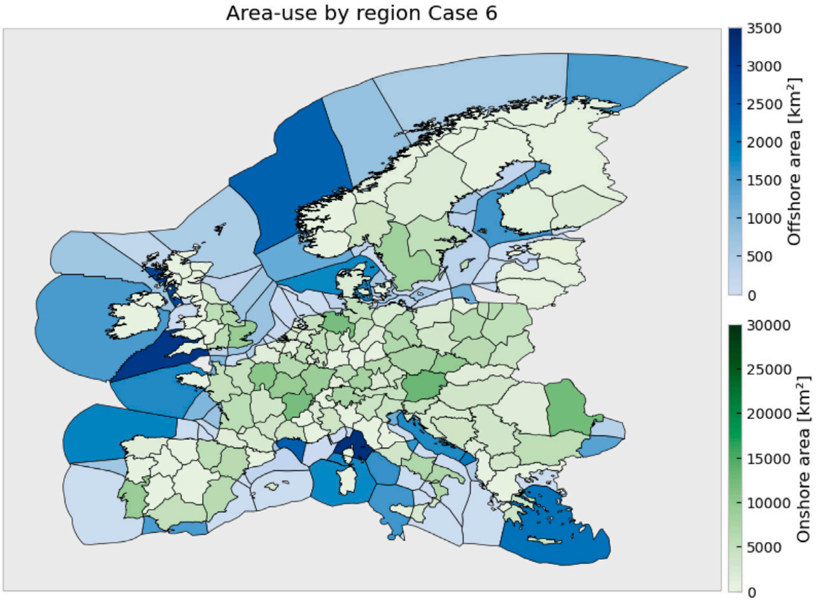
Energy systems driven by coarse climate data (≥10–15 Km) depend more on energy storage and H_2 technologies than renewables. Even for renewables like wave energy, which are currently not fully commercialised, the usage of a high resolution dataset drives installations of wave energy converters up to 22 GW (Case 3, see Fig. 12(a) and Fig. 12(b)).

In terms of availability of the resource, the coarse data (Case 1), see Fig. 15, especially for marine renewables show a persistent under-estimation when compared to Case 5 (see Fig. 16). This is most impactful in wind resources, whilst for wave energy most changes are for the nearshore WEC. It has to be noted, that for the shallow WEC and its depth applicability, the 2 Km dataset can be considered as "coarse", as non-linearity i.e. depth breaking, bottom friction, and triad interactions at depths $\leq$ 20 m are prevalent (see Fig. 16), and require even higher fidelity.

Area usage is also a major deciding factor, that is becoming more relevant for the energy transition. This does not refer to Not In My



(a) Area needed Case 1



(b) Area needed Case 6

Fig. 17. Area coverage per type of generator, aggregate Onshore (onshore wind, solar and solar-HSAT), and Offshore (floating wind, floating solar, offshore wind, tidal, WEC farshore, WEC nearshore, WEC shallow).

Back Yard (NIMBY), but simply to the area that renewable energy generators will require. Of course, proximity to urban areas or cities is likely to lead to more negative permitting issues, but this goes beyond the scope of the study. To estimate the area covered, we have considered the fill factors used in our analysis, and have also clustered the generators to Onshore (onshore wind, solar and solar-HSAT), and Offshore (floating wind, floating solar, offshore wind, tidal, WEC farshore, WEC nearshore, WEC shallow). In Table 3 all aggregated installed capacities and required areas have been estimated, Case 1 (coarse) shows the most area-intensive onshore solution, with 665 thousand Km^2 to accommodate 1812 GW, and in total Case 1 system needs ≈667 thousand Km^2. When marine renewables are deployed, the packing density and hence area required is significant less, as evident in the 2030 system of Case 5 that only requires in total 243 thousand Km^2 (onshore 228 thousand Km^2 and 14 thousand Km^2).

For 2050 the efficiency of the marine area utilisation is most prevalent by the reduction in onshore areas used, keeping in mind that the demand has increased by 40% for the system. The areas needed to cover a 2050 system is ≈468 thousand Km^2 reflecting a reduction of total area needed of 30%. The reduced area in onshore areas in immediately evident, and highlights one of the key opportunities that lay in marine renewables (see Fig. 17), the reduction of area strain for capacity deployment and potential NIMBYism.

4. Discussion

The value of marine renewables has not been thoroughly investigated, and they are often overlooked. Europe is aiming for a carbon neutral energy system, and that can be achieved by utilisation of indigenous renewable energy sources, that are safer and can prove

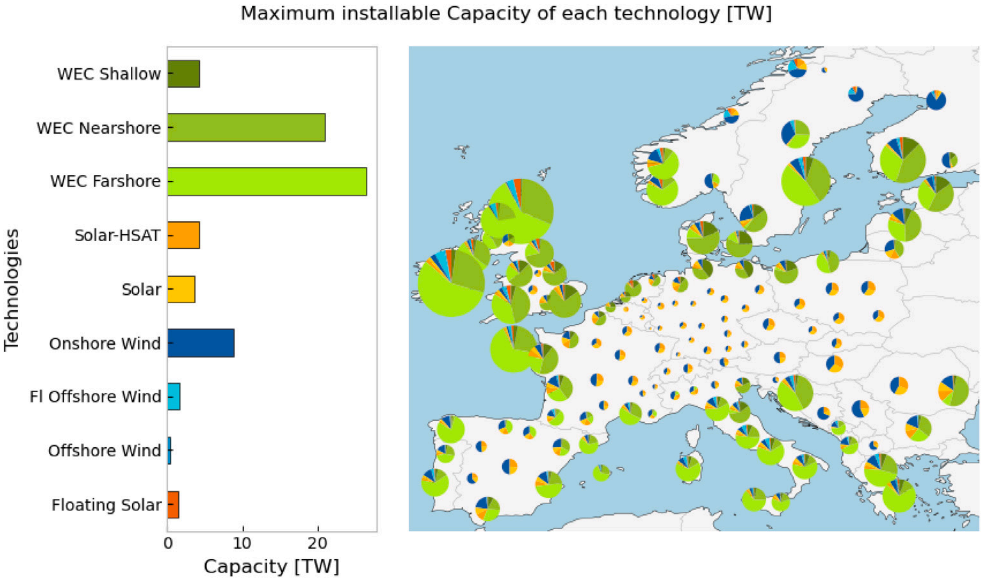


Fig. 18. Maximum installable capacity per technology, as estimated by the model, not accounting to costs.

reliable. Advancing the Energy Transition means that massive amounts of installations are expected, however, it is often forgotten that such development may bring local/regional/country pushback. Not In My Back Yard (NIMBY), can often prove detrimental to new energy developments. Moving offshore not only allows us to access higher density resources, but also larger free areas close to population centres. Marine renewables have a higher packing density, and thus maybe able to achieve higher production with less area, Fig. 18 shows the maximum installable capacity (not to be confused with actual installed), highlighting higher capacity density per Km^2.

The fidelity of resource data can have large impacts on the effectiveness of calculations for renewable energies as shown by the installed generator capacities per technology of the different cases. Coarser datasets incapable to capture smaller scale changes and variations as fast. In addition, local orographic/bathymetric characteristics are aggregated, in large datasets, leading to misleading conditions. Although, it is often that grid congestion, and buses availability are the main topic of research, the climatic conditions are as important. Good high quality datasets, clearly show that multi-generational renewable energy systems are viable, and can actually reduce the need for large scale energy storage.

Reducing storage requirements in the overall energy system especially in the form of batteries, is not only beneficial for reducing system costs, but is an important aspect when critical material intensity of the energy system is regarded. An energy transition towards a 100% renewable system relies heavily on critical materials across various different key technologies like wind turbines, solar PV, transmission infrastructure but especially electro chemical batteries [72]. Most critical raw materials cannot be sourced in Europe, creating international dependencies [73]. Technologies reducing this dependency are therefore a valuable alternative, from a geopolitical but also global perspective, in order to reduce resource constraints.

In addition, to the benefits of wave energy reducing needs for battery storage, the technology could potentially act as a largely European sourced renewable energy alternative, if generator technology that does not rely on Rare Earth Elements (REE) is adopted. This could be a major advantage over current offshore wind, which relies heavily on strong permanent magnets (PMs) with high REE intensities, and solar PV with high critical material requirements and mostly Asian-centric manufacturing capabilities.

While the study tried to present the benefits of marine renewables, we still have to address limitations on the matter. First and foremost, regardless of the resolution the same approach has to be repeated numerous times, within a Climatic Window (30 years), to ensure that "worst case" climate scenario will still lead to a stable system. In addition, with the introduction of high resolution datasets, we also need to enhance the representation of local natural and man-made structures, that will add turbidity or act as diffraction (sink) sources.

Dependencies in costs and deployment conditions also can be a major mode of uncertainty, which we aim to address in future work. Extrapolating costs and reduction pathways for the future can be taunting and can heavily depend on supply chain disruptions. Often times for developing technologies, i.e. WECs, floating wind, the assumptions on deployment rates will be very sensitive to market conditions. Therefore, although we can assume a constant or variable (as in this case) learning rate, the actual deployment may deviate. These will have an effect on deployment potential, for WECs especially, since the model is partially cost driven over-estimating costs may lead to reduction in installations. On the other hand, using very "optimistic" learning rates can lead to solutions that provide un-realistically low costs, or achieve high capacities in very few years. This without taking into account the deployment capacity and infrastructure lead times. Finally, we also observed through our results that the grid expansion often favours bus and grid elements onshore, hence the connection points and discretisation of coastal and offshore areas needs further attention.

5. Conclusions

In this study, the important role that marine renewables can play in the 100% renewable energy system of the future is underlined. A major finding was the immense impact that high-resolution climate data have on the Energy Transition and future studies. The spatial resolution and quality of the data, allows physical non-linearities to be better resolved, this hold true to wind and wave datasets. A higher temporal resolution allows the generators to capture regional variabilities in intensity. Both of these elements translate into better evaluation of power production opportunities and have shown to lead to a reduction of more than 50% of installed capacity required, whilst the curtailments are reduced ≈40%, these was evident by the impacts of higher wind and wave resolution datasets.

Multi-generation systems are known to have immense benefits, but when large ESMs are used, these benefits seem to diminish. A 2030 parametric approach combination of cost driven approaches and a coarse dataset, seem to predominately favour onshore generators (1.9

TW in total) and energy storage. When the model is driven by coarse data the majority of installed capacity is onshore wind (1.44 TW) and solar (0.37 TW), with a significant amount of H_2 storage (93 GW) and batteries (92 GW).

Higher spatial fidelity climate data allow for better representation of non-linearities, and can mitigate the underestimations of the resource. This leads to installing less renewable energy generators but their usage is far more efficient with less curtailments. When higher resolution wind alone is used, onshore generator capacity falls to 705 GW, batteries to 60 GW and H_2 to zero. Once high resolution wave data alone are used, for the first time in literature, a significant amount of wave energy renewables is installed, specifically 22 GW, even with the higher costs of 2030.

Following, the Offshore Energy Strategy 2030 was implemented into the model with the use of high resolution wind and wave datasets, this significantly improved the spatial distribution of renewable generators and allowed for (mostly coastal) regions to attain a more diverse profile. Floating wind installed 46 GW, bottom fixed wind 64 GW, wave energy 6 GW, and onshore renewables 650 GW. This system, showed 40% curtailment reduction leading to energy storage being deployed. The role of battery storage is still important with 50 GW, however without the existence of H_2 systems. In terms of costs, a multi-generation 2030 Energy System seems highly more beneficial, as it reduces the amount of energy storage without compromising satisfaction of demand, for Case 1 (coarse) system the costs due to over-capacity and ample storage are 295 billion €, whilst for the multi-generation with marine renewables the cost is 156 billion €, which is a reduction of 47%.

Similarly, for 2050 marine renewables allow for the system to mostly operate on many generators, for onshore the system requires 1.1 TW, for marine 0.5 TW, for a total capacity of 1.6 TW with a demand increased by 40% (based on 2020 consumption). However, the cost of the system amounts up to 364 billion €, increased by 20% when compared to coarse Case 1 (295 billion €). The area required for marine renewables is 53,182 Km^2 and offshore 414,876 Km^2, underlying the untapped opportunity for deploying more marine renewable energies as they have higher energy density.

The deployment of marine renewables according to the Offshore Energy Strategy (OES) also have impacts on the reduction pathways of the generators. This translates into significant learning by doing reductions, and depending on the WEC 2050 capital expenditure are 1.5 million €/MW, 1.17 million €/MW, and 892 thousand €/MW, for farshore, nearshore and shallow respectively. Similarly, due to the OES, the floating wind also reach 2.2 million €/MW.

High resolution datasets have an obvious benefit in deploying multiple generators, and are able to satisfy current and future demand with less costs and higher energy independence per country. Higher spatio-temporal dataset are suggested to be used when modelling 100% renewable systems, and spatial resolution should not be coarser than 10 Km for wind, coarser than 5 Km for wave energy, and coarser than 2 Km for tidal energy.

CRediT authorship contribution statement

George Lavidas: Writing – original draft, Validation, Resources, Investigation, Data curation, Writing – review & editing, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Lefteris Mezilis:** Visualization, Resources, Data curation, Writing – review & editing, Software, Investigation. **Matías Alday G.:** Writing – original draft, Resources, Writing – review & editing, Software. **Harish Baki:** Writing – original draft, Resources, Writing – review & editing, Software. **Jian Tan:** Writing – original draft, Resources, Writing – review & editing, Software. **Avni Jain:** Writing – original draft, Resources, Writing – review & editing, Software. **Tabea Engelfried:** Writing – review & editing, Resources, Writing – original draft. **Vaibhav Raghavan:** Writing – review & editing, Resources, Writing – original draft, Formal analysis.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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