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Trends in Renewable Energies Offshore – Guedes Soares (Ed)

Wave energy and the European transmission system

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ABSTRACT: Many questions remain regarding the exploitation of wave energy and its interaction with our energy systems. Particularly about their likely role in future multi-renewable power systems, given the resource's abundance, predictability, and high energy density. The objective of this paper is to present the expansion of the renewable energy capabilities of an open-source dynamic energy system model with novel wave energy converters subroutines paired with high-resolution metocean from the ERA5. The expansion allows for the model to assess the wave energy technical resource across Europe's coastlines; Estimate the renewable wave energy capacity potential; Derive renewable wave generation availability time series of different devices; And consider wave energy technologies in a power flow optimization of the European transmission grid. It establishes the basis to perform future exploratory investigations of wave energy converters under a high renewable European electricity grid.

1 INTRODUCTION

The release of the 6th assessment report by the IPCC has highlighted once more the urgent need to decarbonize our energy systems if we are to reach the global agreement to limit global warming below 2 degrees below pre-industrial levels (United Nations 2015). Exploitation of all available renewable energy resources is a necessary step towards the substitution of fossil fuels and decarbonization of our energy systems.

The energy transition is currently being led by mature renewables such as hydro, solar, and wind, but they come with setbacks of their own due to their intermittent nature, leading to challenges to maintain flexibility and power stability (Lavidas & Blok 2021). As countries move towards energy systems with high share of renewables these issues will become increasingly relevant, demanding power flexibility in the form of electricity storage.

Multi-renewable energy systems, which must consider emerging technologies that exploit other available renewable energy resources have the potential to reduce the variability of these mature renewable technologies (Lavidas & Blok 2021) and increase the substitution of fossil fuel in the system.

Marine renewable technologies can represent an important part of these multi-renewable energy system and are increasingly perceived as an essential piece towards the decarbonization of the energy system. In fact, Ocean wave energy is an abundant and predictable resource. "Its global theoretical potential is 29.5 PWh yr-1 (106 EJ yr-1 27), meaning that ocean energy alone could meet all global energy demand (Mørk et al. 2010, IRENA 2020)." Due to its predictability and more stable generation than other renewable energy sources, ocean energy could support and stabilize grids that integrate variable renewable energy sources, such as wind and solar PV" (IRENA 2020).

In their research, Jacobson et al. (2017) underlined the vital role that offshore renewables must play under a feasible carbon-free energy system and suggested that ocean energies are expected to play a significant part.

Wave energy has the second largest among all ocean renewable energy sources (Aderinto & Li 2018). It is one of the most dense, predictable, and persistent energy sources. Furthermore, multiple regions and countries are exposed to it and can exploit wave and other ocean resources to meet their energy needs and decarbonization targets. This is especially relevant for islands and remote coastal areas, which commonly have high and volatile energy costs and have limited land availability.

"Many countries have seen some development in the planning, installation, and operation of wave energy converters. Although the amount is still low compared to other renewable energy sources, such as solar and wind, the progress shows that interests and awareness in the ocean wave energy as a viable source of energy are increasing." (Aderinto & Li 2018).

Given the 2015 Paris Agreement, and the targets set by the European Commission to achieve carbon neutrality by 2050 via its Green New Deal

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(European Commission 2018), it is paramount for governments to properly consider and assess the potential opportunities and challenges that the integration of wave and other marine renewable energies imply in the energy system and future expansion and capacity planning of the system.

In this paper we present the expansion of the renewable energy capabilities of PyPSA-Eur, an open model dataset of the European power system formulated within the Python for Power System Analysis (PyPSA) framework (Brown et al. 2018) with novel wave energy converters subroutines paired with metocean data from the ERA5. This wave energy addition establishes the basis for future exploratory investigation of the interactions and hidden opportunities of wave energy converters in a wider context under a high renewable system on the European Electricity Grid.

The paper is structured as follows; The methodology section gives background information on the PyPSA-Eur model workflow and the wave resource assessment and potential energy production. This is followed by the results of the initial integration, where preliminary results of the extended renewable capacities of the model are presented. The discussion section examines the implications, advantages, and limitations of the Wave Energy Converters (WEC) integration, as well as restating the existing limitations of the PyPSA-Eur model. Lastly, concluding remarks and future work is discussed.

2 METHODOLOGY

2.1 *PyPSA-EUR*

A critical part of this study was the development and integration of representative WECs in the existing dynamic energy system model, PyPSA-Eur, an open-source model dataset and optimization specific for the European power system at the transmission network level which covers the whole European Network of Transmission System Operators for Electricity (ENTSO-e) area (Hörsch et al. 2018). The model is built on top the Python for Power System Analysis (PyPSA) software, "an open software toolbox for simulating and optimising modern electrical power systems over multiple periods" (Brown et al. 2018).

PyPSA-Eur and its dataset include models, assumption for conventional generators, renewable generators, storage units and network and transmission lines. It is suitable for both operational studies and generation and transmission expansion planning studies. (Hörsch et al. 2018).

PyPSA accommodates different renewables, such as solar photovoltaic, wind turbines, solar thermal collectors, among other renewables. For the first time a WEC was integrated into PyPSA, allowing for the first time to assess the impact of wave energy into the European power grid. The extended model was executed for the first time under a 100% renewable scenario under the 2013 weather conditions. The reason of the used year is due to the fact that PyPSA has been validated for that year (Hörsch et al. 2018). This excluded conventional carriers except for existing geothermal and hydroelectric plants. It also included storage in the form of Hydrogen (H2), pumped hydro storage and batteries as modeled in the original PyPSA-Eur. In that sense, the model assessed and optimized the deployment of solar, onshore & offshore wind, and wave energy generators under the ENTSO-E network topology of the same year.

2.2 *Wave Energy Converters Generation*

For the proper deployment of WECs, wave resource characterization plays an important role to develop strategies for WEC deployment as it identifies appropriate locations for the devices as well as optimizing or selecting a suitable WEC for that location, considering costs, environmental conditions, and available power.

For this study, three different WECs where integrated into the model; a Farshore 750kW device which operates on depths below sea level ranging from 50-150 m, this is represented by the Pelamis an articulated attenuator with length 140-180m and 4m in diameter. A 1 MW Nearshore device operating in depths ranging from 20-80m, represented by a point absorber with a diameter of 20 meter; and lastly a Shallow 600kW device operating in shallow waters with a maximum depth of 20 m, represented by a terminator surge-oriented device.

Wave energy resource assessment focuses on the characterization of the dominant metocean conditions and the energy potential (Guillou et al. 2020). The metocean characteristics H_{m0} and T_{peak} allow for the determination of the power production potential of a wave WEC at a given sea state. To assess the power production potential of the devices within the Atlite module of PyPSA-Eur, the power matrix defined for each device is employed.

A WEC power matrix is the equivalent to a power curve, and it is used to estimate the production of carbon free electricity per sea state (Lavidas & Kamranzad, 2020), which is characterized by the combination of significant wave height (H_{m0}) and peak wave period ($T_{peak)}$ at each grid cell and time step.

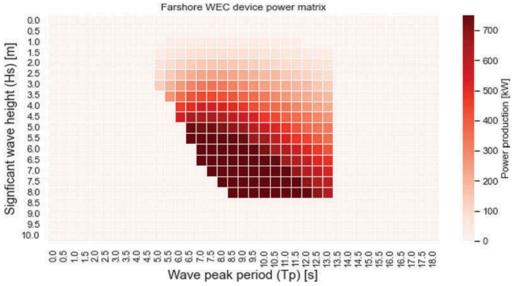

Figure 1. Farshore Wave Energy Converter Power Matrix. Range depth 50-150 m.

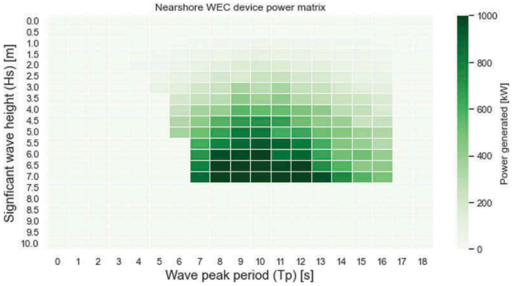

Figure 2. Nearshore Wave Energy Converter Power Matrix. Range depth 20-80 m.

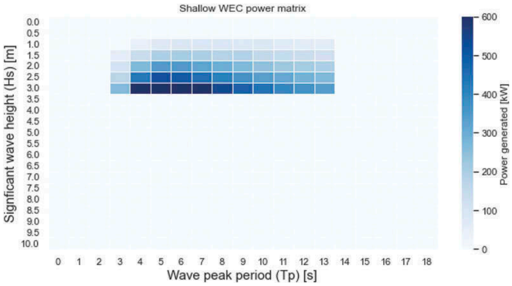

Figure 3. Shallow Wave Energy Converter Power Matrix. Range depth 50-150 m.

The power matrices of the devices that have been integrated into the model are shown in Figures 1–3. It can be observed that the different devices generate their maximum power output at different wave heights and peak wave periods. The Farshore device, which operates at depths from 50 to 150 m, is optimized to generate its maximum output at wave heights between 5 and 8 m and wave peak periods ranging from 6 to 12.5 seconds. Meanwhile, the nearshore device produces its maximum output on wave heights between 6 and 7 meters and between wave periods of 8 and 13 seconds. The shallow device is optimized for milder conditions, where the power can be generated by the device in sea states characterized between 1 and 3 meters wave height and wave periods ranging from 3 to 14 seconds.

The WEC function incorporated in PyPSA is subsequently coupled with the metocean conditions of every sea state at every grid cell and time step obtained from ECMWF's re-analysis ERA5 dataset (Hersbach et al. 2020), allowing us to estimate the capacity factor of each raster cell. In our consideration, the usable area i.e., how much is the maximum installed wave generation capacity is computed, here a packing density of 20MW/km^2 was considered as feasible by Lavidas & Blok (2021).

The usable area for WECs is restricted by the operational water depths determined for each device. In addition, all nature reserves and restricted areas listed in the Natura2000 database are excluded. The wave geographic generation potentials are shown in Figures 4–6 for the different devices.

Because PyPSA-Eur partitions the different countries into Voronoi cells and the cutout of the weather data is finer than them, it estimates the distribution of generators across the grid cells within each Voronoi cell. To compute this generator layout, the installable potential is multiplied with the capacity factor at each grid cell. This follows the logic to install more generators at cells with a higher capacity factor. Once this layout is computed it is used to calculate the generation availability time series. Further information on the PyPSA-Eur workflow can be found Hörsch et al. (2018) and Brown et al. (2018).

3 RESULTS

The novel integration of WECs into the PyPSA-Eur allowed for the first power analysis software to assess the wave energy resource across Europe's coastlines. The extended PyPSA-Eur model was executed for the first time under a 100% renewable scenario under the 2013 weather conditions, and with wave energy considerations.

Conventional carriers where not part of the network, as we envisage a net zero energy system for Europe utilizing all indigenous renewable energy sources. Only existing geothermal and Hydroelectric plants where considered. The model assessed and optimized the deployment of solar, onshore & offshore wind, and wave energy generators under the ENTSO-E network topology of the same year. Allowing to perform a cost-based power flow optimization of the system.

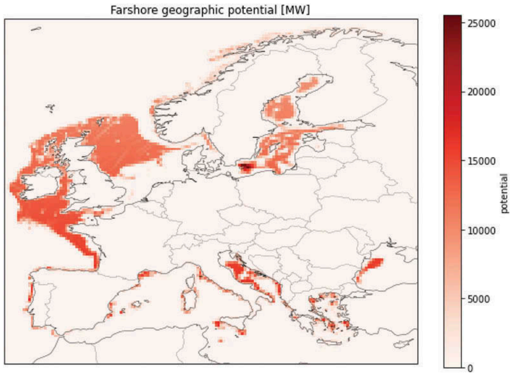

Figure 4. Farshore WEC maximum installable capacity per cutout grid cell after land use restrictions in Europe.

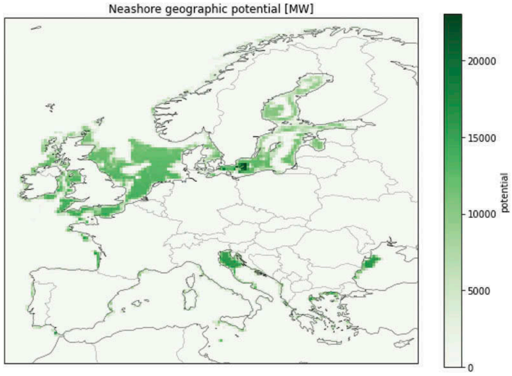

Figure 5. Nearshore WEC maximum installable capacity per cutout grid cell after land use restrictions in Europe.

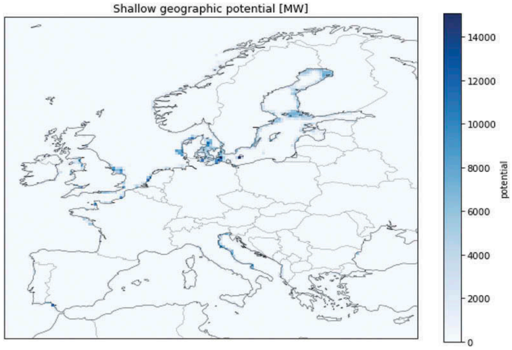

Figure 6. Shallow WEC maximum installable capacity per cutout grid cell after land use restrictions in Europe.

During the execution of the model, the European network topology was clustered down into 37 nodes, approximately one node per country, where the buses, generators and transmission corridors are aggregated. Information on the clustering of the network is documented in Hörsch et al (2018).

It is important to highlight that wave resource potential, and, thus, potential power production of WECs, vary both spatially even in close proximity, as well as temporally across months, seasons, and years. Furthermore, the resolution of ERA5 is not advised for nearshore and shallow water converters, as both the underlying wave model and its spatial resolution is not advised to perform wave energy analysis (Guillou et al. 2020, Lavidas & Venugopal 2018).

Nonetheless, knowing these limitations, the modifications added to PyPSA-Eur allow for the software to estimate the wave energy resource capacity potentials and derive renewable wave availability time-series from re-analysis weather dataset ERA5 across Europe, coupled with the European power system at the transmission network level covering the ENTSO-E area.

Figures 4–6 visualize the geographic potential of the maximum installable capacities of each WEC device. In reality, the installed potential will depend on a variety of factors such as array types, WEC design, packing density and marine spatial planning (i.e., colocation options). However, given our configured constraints for each device, the model calculated a maximum installable potential of 20.26 TW across all of Europe for the Farshore device. Approximately 14.68 TW of maximum installable potential were calculated for the Nearshore device, and 2.4 TW for the WEC shallow device.

Moreover, Figure 7 showcases the maximum installable potentials by country. It can be observed that Great Britain has the highest potential for both the Farshore and Nearshore device, with installable capacity of 6.3 TW and 3.6 TW, respectively. Meanwhile, for the shallow device, Sweden, Finland, and Denmark have the highest installable potentials close to 400 TW. These values represent the maximum extendable capacity of the wave energy converters that the PyPSA-Eur considers during the optimization.

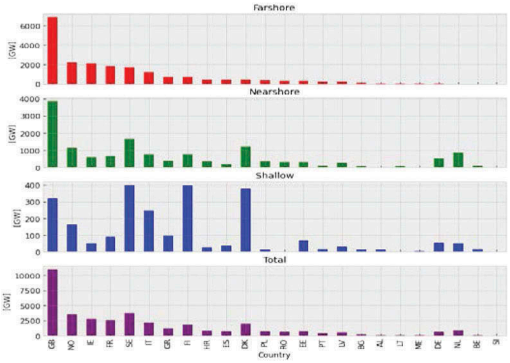

Figure 7. Maximum installable capacity of WEC devices by countries.

The expansion of wave, wind and solar according to the geographic potentials computed are dependent on technical, environmental, and political constraints (Horsch et al. 2018). In the real world, this implies a balance not only between land availability, but also conservation efforts, landscape impact, social acceptance, and political will.

As mentioned before, the geographic potentials estimated are only dependent on the 20 MW/km^2 packing rate, the depth constraints for each device and the exclusion of restricted areas included in the Natura 2000 database. These potentials do not yet account for resource availability.

To account for resource availability, and create the generator layout used in the optimization, the model computes the resource availability time series per unit of nominal capacity at each location. Allowing to compute the average capacity factor for the year 2013, based on the characterized sea states for every cell and time step, visualized in Figures 8–10. The different average capacity factors of eligible

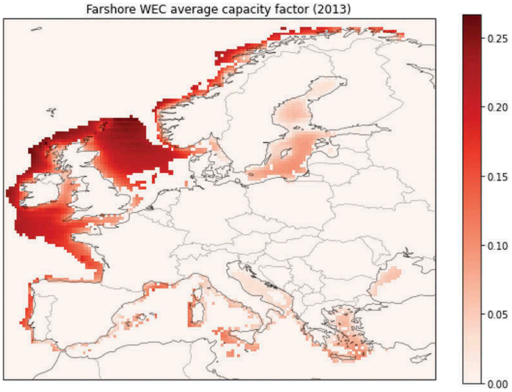

Figure 8. Farshore Wave Energy Converter yearly (2013) average capacity factor in Europe in potential locations.

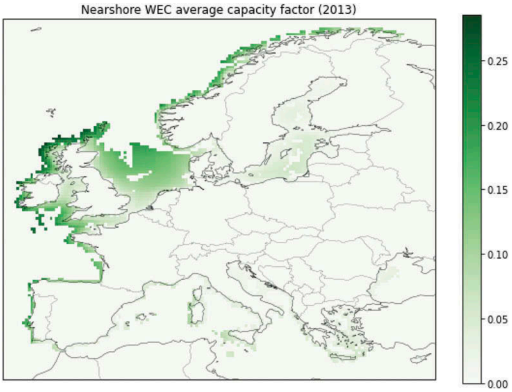

Figure 9. Nearshore Wave Energy Converter yearly (2013) average capacity factor in Europe in potential locations.

geographic locations can be observed. The highest capacity factors for the Farshore device for the year 2013 can be found in the Atlantic Ocean and north of the North Sea, averaging between 20-25%.

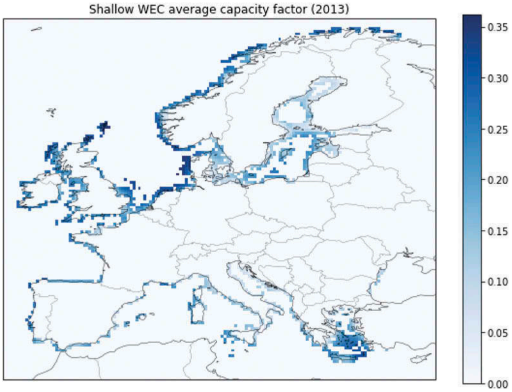

Figure 10. Shallow Wave Energy Converter yearly (2013) average capacity factor in Europe in potential locations.

Meanwhile, a nearshore device in the year 2013 would showcase an average capacity factor above 25% if placed on coasts north-east of United Kingdom and Ireland according to its power matrix and the average sea states during that year. While a shallow device, although more restricted by land eligibility, can potentially have average capacity factors between 30% and 35% in various coastlines of Europe, highlighting The Netherlands' North Sea coastline, the Norwegian Sea, and the Cretan Sea.

Additionally, Figure 11 showcases an illustrative example of the power availability time series for the month of March 2013 computed by the model according to the metocean conditions for the three types of devices in Great Britain.

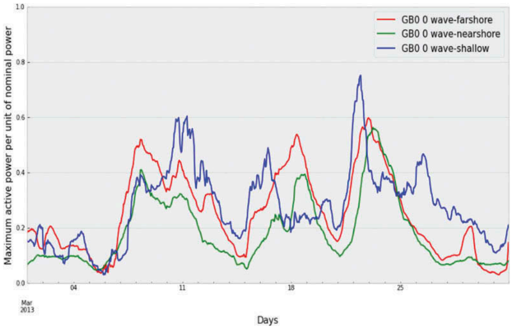

Figure 11. Active Power Availability Time Series for WEC devices in United Kingdom, March 2013.

Regarding the initial Power Flow optimization results, only 8 MW of wave energy generators were considered in the linear optimal solution. While in terms of other renewables the model installs 962 GW of onshore wind, 438 GW of solar, 33 GW of offshore wind, and 99.5 GW of hydroelectric generators across Europe, with additional storage capacities of 54.6 GW of pumped-hydro, 19,170 GW of H_2 and 104 GW of batteries.

These initial results are practically equivalent to the case where the wave energy resource is not considered, as a minimum amount of wave generators was considered in the solution.

This can be attributed to the fact that the costs of WECs considered for the optimization are significantly higher than competing renewables, were not identified based on experience curves, similar to the other technologies in PyPSA and have not been optimally tuned. These costs will vary per WEC type and hence requirements (cabling, connection cost, etc.). and will have a significant effect on the cost minimization optimization and subsequently in the potential for deployment. Future work includes better definition of costs for different WECs and correspondence with the 2030 costs of other technologies.

4 DISCUSSION/CONCLUSIONS

The present research has undertaken the expansion of the renewable energy capabilities of the open-source energy model PyPSA-Eur. This has been accomplished by the novel integration of three different Wave Energy Converters subroutines coupled with high-resolution metocean from the ERA5.

This integration has allowed for the model to assess the wave energy resource across Europe's coastlines characterized by the bivariate joint distribution of H_{m0} and T_{peak} gathered from ERA5; estimate the renewable wave energy capacity potentials restricted by depth, packing rate, and land availability; Derive renewable wave generation availability time series of the WEC devices according to their power matrixes and the characterized sea-states; and consider the wave energy resource and technologies in a power flow optimization of the European transmission grid.

The current focus of the research and the initial results presented was on the expanded resource assessment capabilities, and the testing and adaptation of the wave energy devices in the energy system model. The model is now capable of assessing metocean data and convert it into power generation potential deriving time-series availability of the wave energy resource. Nonetheless, further refinement and research, especially on the power optimization parameters and assumptions of the model is still needed to fully assess the integration of wave energy converters into the PyPSA-Eur model. In our next steps we aim to introduce high spatio-temporal wave data for all European coastlines and, estimate the economics of WECs in better granularity.

Nonetheless, the expansion of the model is not without limitations, not only regarding the wave energy resource addition, but also including the limitations already present in the PyPSA-Eur model.

In this research only H_{m0} and T_{peak} were employed to characterize a sea-state and thus power generation potential. However, various other sea-state characteristics can influence the choice of an appropriate wave-energy site. Wave direction is an important factor to consider for the optimal design and placement of wave energy devices. Places with low variability in direction may be preferable. Furthermore, "Spectral properties of the sea state can also influence WEC power output and hence design" (Fairley et al. 2020). This limitation is further highlighted by the fact that there has been no convergence of WEC designs, and this research employs 3 different power matrices representing a design for different depths. In addition, and as previously mentioned, Guillou et al. (2020) highlights that the resolution of ERA5 is not advised for nearshore and shallow wave converters.

Another important limitation of the current research is that the analysis has only been performed with data from the year 2013. However, it is important to consider the monthly, seasonal, and annual variability of WEC performance to properly assess the wave resource. Highlighting that the technical specification by the International Electrotechnical Commission, recommends that a wave energy resource assessment should cover a minimum of ten years on a minimum temporal resolution of three hours (Guillou et al. 2020).

From the original PyPSA-Eur model, further limitations are still present, for instance; approximations made due to missing data and the topology of the ENTSO-E area; The use of Voronoi cells ignores the topology of the underlying distribution network; assumptions about the distribution of load proportional to population and GDP; and limited of information on existing power plants, including hydro. (Hörsch et al 2018).

Nonetheless, the open-source nature of PyPSA-Eur allowed for its further development to include wave energy resource through this research and it is hoped that this work will serve as a steppingstone for future research on ocean energy and future expansion planning studies.

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