Integration of wave energy into Energy Systems
an insight to the system dynamics and ways forward

Lavidas, George; Delgado Elizundia, Felix; Blok, Kornelis

DOI
10.36688/ewtec-2023-157

Publication date
2023

Document Version
Final published version

Published in
Vol. 15 (2023): Proceedings of the European Wave and Tidal Energy Conference

Integration of wave energy into Energy Systems: an insight to the system dynamics and ways forward

George Lavidas, Felix Delgado Elizundia, and Kornelis Blok

***Abstract*—Wave energy is a rich and highly accessible renewable energy resource, that has largely been underdeveloped. Studies from the sector have tried to show the potential of benefits wave energy in "simple cases" or via small hybrid systems, the large scale incorporation of wave energy has not yet been fully investigated. Our approach uses a fully dynamic climate driven energy system model, which has undergone modifications to include wave energy converters and their associated dependencies. This study explores the system dynamics and important elements that will be used for large scale wave energy integration; in a fully coupled European Energy System. We explore the cost pathways of different wave energy converters, the impact of climate data, and the impact of transmission capacity expansion under cost-optimal configurations of a multi-renewable European power system. From this preliminary approach we aim to provide the boundary conditions, and assumptions that will govern the integration of wave energy into the European Energy System up to 2050.**

***Index Terms*—Wave energy, energy system modelling, experience curves, economics**

I. Introduction

THE sixth (6^{th}) report of the Intergovernmental Panel on Climate Change (IPCC) has strongly highlighted that it is urgent to decarbonise our energy systems, if we aim to limit global warming below 2° C degrees above pre-industrial levels [1]. Although, the same cautionary points lead to the 2015 Conference of Parties (COP21) commitments in Paris, the rate of decarbonisation is still not adequate [1], [2].

The energy transition is currently being led by mature renewables such as hydro, solar, and wind, but they come with shortcomings of their own due to their intermittent nature, leading to challenges in order maintain flexibility and power stability.

The work has been a part of the EU-SCORES project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036457.

George Lavidas is an Assistant Professor at the Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands. He leads the Marine Renewable Energies Lab (www.tudelft.nl/ceg/mrel) (e-mail: g.lavidas@tudelft.nl).

Felix Delgado Elizundia is a research assistant at the Marine Renewable Energies Lab, at Delft University of Technology (e-mail: f.delgadoelizundia@student.tudelft.nl).

Kornelis Blok Professor of Energy Systems Analysis, and Head of the Energy and Industry group, at the Faculty of Technology, Policy and Management, Delft University of Technology, The Netherlands (e-mail: K.Blok@tudelft.nl)

Digital Object Identifier:
https://doi.org/10.36688/ewtec-2023-paper-157

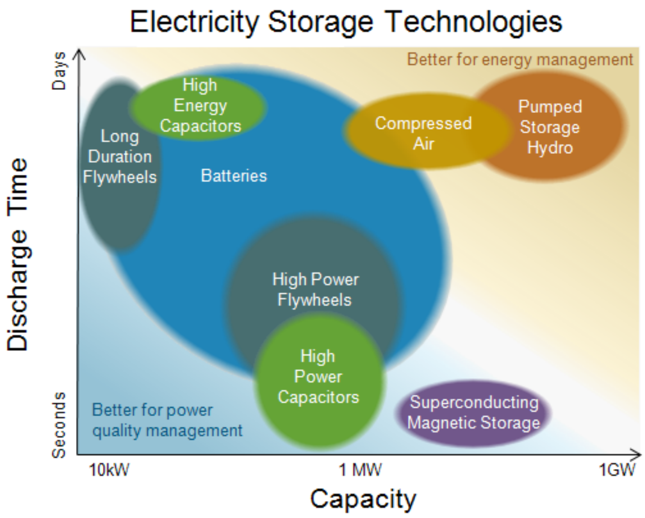

Fig. 1. Approximate representation of each storage type's technological characteristics for time duration and power output [6]

These shortcomings will be further amplified as their share in the electricity system increases. Although, energy storage can offer short-term flexibility for these mature renewables, associated costs of current "renewable feed" battery systems are from 1500-3000 €/kWh) [3]. However, effective long term grid control (bulk management, slow response) can occur via using compressed air energy storage (CAES), and/or pump hydro-electric systems (PHS), and/or thermal storage with power conversion, and/or hydrogen with power conversion. Batteries and flow-batteries (a subcategory included in the definition of Batteries) can be can be an option, but their costs (€/kWh) and land requirements can be prohibitive [4], [5].

Multi-renewable energy systems,including emerging technologies, have the potential to reduce the variability of these technologies, increase power availability, accelerate the substitution of fossil fuels and offer additional benefits social benefits [7], [8].

Marine energy is increasingly being perceived as an important piece of future energy systems, given they are characterized by a stable generation profile, predictability, and high energy density. Furthermore, marine renewable resources are more persistent and have higher temporal availability compared to solar and wind resources [9]–[12].

As mature renewable technologies increase their share in existing energy systems, the intermittency of solar and wind introduces volatility and unpredictability to the system, leading to potential mismatches between demand and supply. Given this, marine energy can support the stabilization of renewable energy power systems with multiple variable renewable energy sources [10], [12]. Bhattacharya et al. [9], highlighted that a system with solar, wind, and marine energy presents reduced generation volatility than a system with only solar and wind, which translate into alleviating balancing costs and reducing price volatility. Furthermore, stating that it is expected that these benefits to be more pronounced as renewable energy deployment increases.

Furthermore, multi-renewable energy systems, which include marine energy, are linked to the advancement of multiple United Nations Sustainable Development Goals (SDGs), such as SDG 7-Affordable and Clean energy, and SDG 13 - Climate Action. Furthermore, renewable energy penetration increases energy diversity, supports decarbonization targets, and reduces import dependency. The latter is particularly relevant for Europe given the recent developments of the Russian-Ukraine war and the respective implications on energy imports, highlighting the need to end Europe's dependence on Russian fossil fuels.

Recently, Potapenko et al. [13], Rojas et al. [14] examined the integration of wave energy into energy systems for various regions, underlying the positive potential role of wave energy.

A. Novelty

In this study we will briefly present a heavily modified fully dynamic and climate driven Energy System model (PyPSA-MREL-TUD) based on Python for Power System Analysis for Europe (PyPSA-Eur), that simultaneously includes three different types of wave energy converters. Unlike, past efforts we have used a pure power matrix approach that represents fully the stochastic natures of wave energy, following international research and standards.

Furthermore, we have incorporated floating wind, with additional characterisation for limits of their installation as distances to coast and depth variations.

Subsequently, we apply the new model for the whole European grid to assess the sensitivities and obtain preliminary results for impacts that wave energy will have on country systems. The PyPSA-MREL-TUD runs with a foresight to simulate a 100% European Energy System for the horizon of 2030, 2040 and 2050, considering relevant cost reductions per technology used.

II. Materials and Methods

Python for Power System Analysis (PyPSA) is an investment and operational optimization model of the European power network which minimizes total annual system costs considering the variable and fixed costs of generation, storage, and transmission given a set of technical and physical constraints expressed mathematically. It is a partial equilibrium model that can optimize both short-term operation and long-term investment of the European power system as a linear problem, employing the linear power flow equations [15], [16].

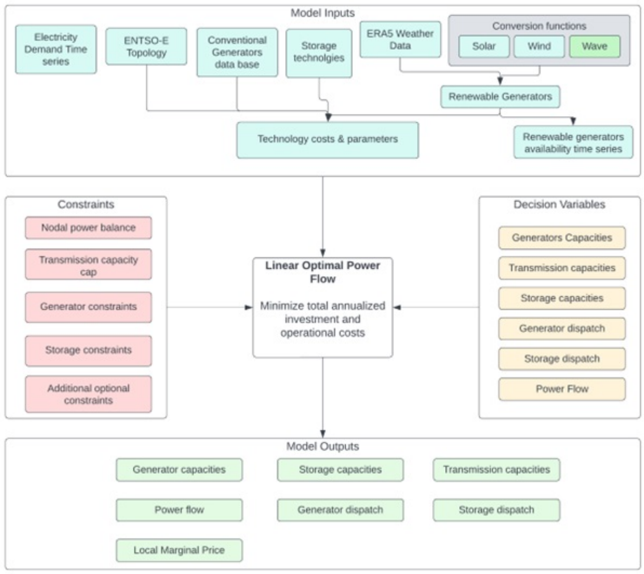

Fig. 2. The pipeline of the PyPSA optimisation approach, now including wave energy

A solved model provides optimized locations of generation, storage, and transmission capacities as well as the optimal dispatch of the components. The model also provides the levels of congestion of the network, levels of curtailment, and nodal electricity prices. Figure 2 presents a general overview of the PyPSA-Eur model, displaying visually the model inputs, outputs, constraints, and decision variables. The overview highlights the novel addition of wave energy, described in the following

To assess the wave power potential within the model, five climate wave variable have been included: Significant wave height (H_{m0}), energy period (T_{m10}), mean zero-crossing (T_{m02}) Peak wave period (T_{peak}), and peak wave direction (Pk_{dir}) (if available in the power matrix). We have also included the option of directionality in the event that a directional power matrix is known. These variables allow for the characterization 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 [17].

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

where ΔT is time, T are either the number of $T_{peak}/T_{m10}/T_{m02}$ and H_{m0}, significant wave heights, and directionality clusters, for different latitudal and longitudal locations (i, j).

A. Wave energy converters (WECs)

Wave energy converters (WEC) are described by different principles of operation, that has lead to variety of devices. Besides, the operational mode of a WEC, the deployment depth are other key distinguishable characteristics of WECs. There are devices suitable for shallow, nearshore, and farshore water conditions, and these are usually related to their power extraction motion [18], [19]. Hence, in order to have a more detailed approach three (3) different WEC are simultaneously considered (see in AppendixA Figure 9):

- a Farshore flexible attenuator (750kW) WEC applicable at depths 50-150 m.
- A Nearshore point absorber WEC (1000 kW) operating in depths ranging from 20-80 m.
- a Shallow (600 kW) device operating in waters with a maximum depth of 20 m, represented by a terminator surge-oriented device.

B. Floating wind

Another modification in the PyPSA pipeline is the inclusion of floating wind. Currently, only bottom fixed wind is included as offshore renewables, but we have opted to also include floating wind concepts in the model to capture the latest developments. While, this is another addition in the model, we do not consider it as not as novel as the WEC integration.

C. Wave climate data sensitivity

Whilst working on the wave energy integration, we encountered that the use of re-analysis datasets is widespread, there are significant drawbacks that much be taken into account While they represent a useful source to draw an initial mapping of the renewable resource, there are some important limitations to consider when interpreting the results of an analysis based on these data sources. For the testing and assessment of PyPSA-MREL-TUD we have used the ERA5 and CFSR database (ERA5 results are presented in this study). However, in the analysis process several observations were noticed.

The first, and probably most obvious limitation is the spatial resolution of global models, typically ranging from 0.5^o to 0.25^o ($\approx 0.3^o$ in the case of ERA5 wave product), which is equivalent to $\approx$ 55 km to $\approx$ 27 km. Thus, it could be generalized 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 [17], [20], [21]

Another important element to take into account, which has a direct impact on the model's output, are the different choices of forcing fields [22]–[24] physical parameterizations and their adjustment to reduce model errors [25]–[28]. The latter point requires special attention, since the "tuning" of models could be done to improve overall performance of wave databases. Such tuning can include the wave growth, quadruplets interactions, non-linear terms, depth induced breaking etc, which can significantly alter the accuracy of a dataset [20]. Hence, wave and wind databases with $\geq$ 20 Km resolution should be used only for reconnaissance energy density characterisations (coarse assessment), and not to operational or power estimates, as they do miss out on many important elements [29].

For further development, the runs of PyPSA-MREL-TUD are planned with use 2 Km wave data and 2-5 km wind data, to minimise discrepancies in resource estimations.

D. Economic sensitivity

As the PyPSA-MREL-TUD model was being developed, we noticed a very sensitive behaviour to the cost modelling assumptions [30]. Given the plethora of options in the 100% renewable energy system, the WEC cost sensitivity is highly influential. Therefore to realistically consider the 2030, 2040 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 its cost but also the cost of competing renewables such as wind and solar, which 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 wave energy devices. Technological learning is modelled through the one variable factor-learning curve approach. 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 upsizing of a product [31].

This approach is utilised to estimate the capital cost of wave energy in the 2030, 2040, 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 the PyPSA-MREL-TUD model, with learning effect, when the cost of the first unit is unknown, 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 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 [31].

A learning curve visualizes 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, a variable learning rate was used to

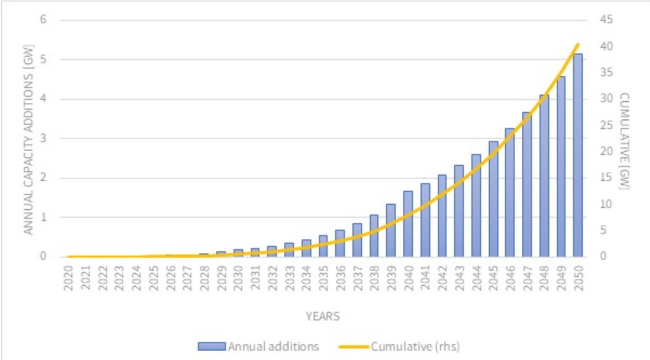

Fig. 3. Total projected capacity additions of wave energy 2020-2050

estimate the potential cost reductions more realistically, with a learning rate of 12% used between 2020 and 2030, 8% between 2030 to 2040, and 4% between 2040 and 2050. A similar approach has been used by Lavidas in 2019 [7], but the reduced effective of the learning rate is to represent the mature renewable energy environment that wave energy is placed. The absence of real learning rates for WECs, and the fact that WECs will not probably follow the steep learning reduction of wind prompted us to apply this conditions. With this approach we are aiming to simulate long-term market conditions, as effectiveness will decrease with more experience gained.

We also took care to project the potential cost reductions in line with the future estimated installed capacity of the Offshore Renewable Energy Strategy, the ambition is to reach 40 GW of installed capacity of ocean energy (such as wave and tidal) by 2050, 1 GW by 2030, and 100 MW by 2025 [32], see Figure 3. The 40GW includes only EU Members States, for the inclusion of the UK we have added another 10 GW. The Offshore Energy Strategy does not differentiate between wave and tidal capacities, but for this effort, we consider that all GW will be wave in Europe as the tidal potential is not integrated into the model yet. Nonetheless, the 1 GW target may even be conservative, as based on announced projects, the ocean energy pipeline expects 2.4 GW in Europe (no technology breakdown information were given) and 2.9 GW worldwide by 2030, in line with the optimistic scenario of the JRC market study on ocean energy [33].

E. Constrains and assumptions

Scope of the study is to test the implementation and explore the hidden value opportunities and implications of wave energy under a 100% multi-renewable power system, under a greenfield approach, and a 2030, 2040, and 2050 horizon.

The geographical scope of the current modelled scenarios is Europe, includes the UK, but more specifically the network topology of the European transmission network ENTSO-E, updated in PyPSA-MREL-TUD until 2019. Under the optimization, new transmission infrastructure cannot be placed, but existing one can be expanded, limiting the total volume of line expansion to 25% of existing line capacities.

All renewable energy technologies and energy storage options available in the conventional PyPSA have been retained as well. Packing densities for WECs follow the suggestion of 20 MW/Km^2 as based in in previous studies that discussed potential packing densities/rates [8], [34].

No limiting capacities of country profile production constrains are considered, and pure energy flow is assumed for Europe. The research and optimization scenarios cover a period of one year, weather, and electricity demand data employed are from the year 2018.

Electricity demand evolve as the years progressed. The scaling factor was estimated using linear regression on historical electricity consumption data of Europe and forecasting it to 2050. Thus, the global scaling factors applied to the scenarios 2030, 2040, and 2050 are 1.10, 1.19, and 1.28, respectively. This simple assumption seeks to represent expected increases in demand, but only considers historical trends. This implies that it does not consider the expected electrification of certain sectors due to decarbonization policies, as well as potential efficiency gains in the future.

The network expansion constraints for 2030 and 2040 are based on the identified cross-border capacity increase needs of ENTSO-E Ten-Year Network Development Plan 2022 (TYNDP), while for 2050 an additional 25% from 2040 estimate was assumed feasible. The TYNDP 2022 study identifies opportunities to make Europe's power system more efficient all over Europe. Specifically, it identified that 64 GW of additional cross-border capacity can be installed on over 50 borders, representing a 55% increase in cross-border capacity. For the decade of 2040, the study identified space for 88 GW of additional cross-border capacity representing a 75% cross-border capacity increase from the current network.

The 55% increase for 2030 and the 75% increase for 2040 were taken as exogenous parameters into the scenarios for their respective horizons. No information was found for the 2050 network, but an additional 25% increase in cross-border capacity over 2040 was considered feasible.

III. Results

The integration of wave energy converters conversion functions in PyPSA-MREL-TUD allowed for the first power analysis software to assess the wave energy resource across Europe's coastlines. It estimated the renewable wave energy capacity potentials restricted by depth, packing rate, and derive the renewable wave generation availability time series of the WEC devices. Subsequently, it derive the capacity factors and power generation potential; and ultimately consider the wave energy resource and WECs in a cost-optimal power flow optimization of the European power system at the transmission network level covering the ENTSO-E area, see Figures 4-5.

The figures showcase the geographic potential of the maximum installable capacities of each WEC device used in the model and averaged capacity factor for the

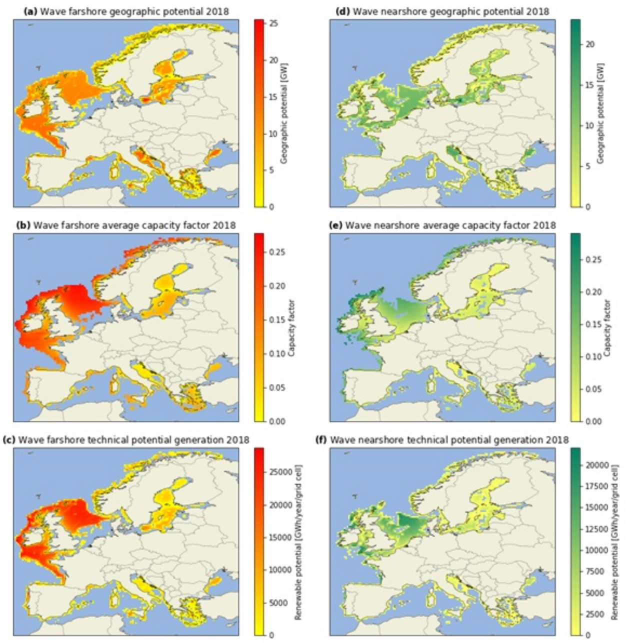

Fig. 4. Geographic capacity potential, yearly averaged capacity factor, and renewable generation potential for the attenuator (a, b, c) and Point Absorber (c, d, f) device, 2018 Europe

selected year. It is important to note that this is not the final installed capacities, but what can ideally be installed. This is repeated for every technology. Combination of the maximum geographic capacity from the assumed land sea, depth restricted areas, the yearly capacity factor, the technical maximum energy for each WEC is estimated for the different European coastlines.

The geographic potential refers to the maximum installable capacity given input parameters of maximum and minimum depth, land restrictions, and packing density for each device. In reality, the realized installed potential or practical resource depends on a variety of factors such as array types, WEC design, and packing density, and marine spatial planning (delimits exclusions zones and areas acceptable for installation of wave energy farms). Furthermore, these technical aspects ultimately depend on political, social, economic, and environmental factors implying a balance not only between land availability, but also conservation efforts, landscape impact, social acceptance, and political will.

However, given our configured constraints for each device, Table I presents the total geographic potentials for each device across the 24 countries with eligible areas to exploit wave energy, as well as the European total.

On purely available space (land and/or sea) criteria, the wave energy resource is the most abundant within Europe, especially in coastline countries. The wave resource has the highest geographic potential reaching approximately 20.3 TW, see Table I.

Furthermore, significant differences in the magnitude of available technical potential or energy can be observed between landlocked and coastal countries, driven by both the wave energy and the offshore wind resource. Another, point to note is that the resource potential of run-off rivers and hydro is constant and not

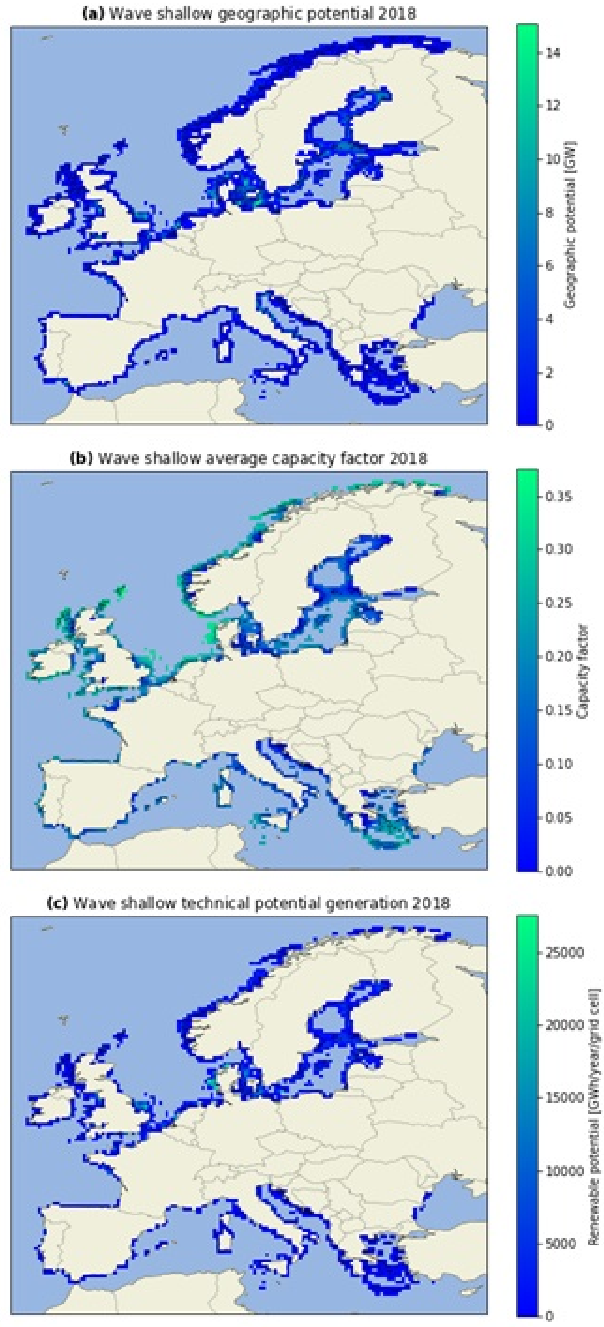

Fig. 5. Geographic capacity potential (a), yearly averaged capacity factor (b), and renewable generation potential (c) for the terminator device, 2018 Europe

affected by Climate Change, however, this, in reality, will not occur as studies have shown that decreases are expected .

Caution is needed while interpreting these figures, as the geographical potentials of each renewable resource can be under conditions aggregated. This is due to the fact that resources may share eligibility criteria for a certain region, such as offshore wind and wave energy, which can be combined. However, in the case between farshore and nearshore wave energy devices, where regions with water depths between 50 and 80 m are eligible for both devices, capacities are not aggregated as they will depend on sitting conditions.

For each scenario, a future, 100% renewable Euro-

TABLE I
GEOGRAPHIC CAPACITY POTENTIALS FOR EACH DEVICE ACROSS EUROPE [MW]

Countries	Farshore	Nearshore	Shallow	Total
Total Europe	20306.9	14690.0	2483.4	37480.3
United Kingdom	6908.0	3855.8	318.4	11082.3
Norway	2255.3	1156.7	165.2	3577.3
Ireland	2125.7	603.2	49.9	2778.7
France	1796.3	654.3	90.3	2540.9
Sweden	1688.1	1672.6	399.8	3760.5
Italy	1179.8	752.3	245.7	2177.8
Greece	744.3	398.0	96.1	1238.4
Finland	684.8	762.0	396.0	1842.8
Croatia	428.6	347.0	24.9	800.5
Spain	423.5	188.1	36.5	648.2
Denmark	389.9	1202.9	377.9	1970.7
Poland	328.3	344.6	11.6	684.6
Romania	299.6	313.7	2.6	615.9
Estonia	295.6	312.1	69.2	677.0
Portugal	236.4	103.5	15.7	355.5
Latvia	222.3	284.8	30.4	537.5
Bulgaria	112.9	91.8	9.9	214.6
Albania	63.3	30.1	13.2	106.6
Lithuania	56.1	91.8	2.2	150.2
Montenegro	52.8	17.5	3.0	73.3
Germany	12.3	520.5	55.6	588.4
Netherlands	2.9	874.0	52.1	929.0
Belgium	N/A	109.7	16.2	125.9
Slovenia	N/A	2.9	0.9	3.7

pean Electricity network was modeled via a greenfield optimization, see Figure 6. The European power system was built from scratch, except for existing hydroelectric and geothermal capacities, which are not extendable during the optimization and remain with a fixed capacity. For other renewables and storage technologies, the installed capacities and their respective dispatch at every time step are optimized depending on the geographical and weather-dependent potentials.

In Figure 6, the node for each country showcases the technology mix of generating and storage technologies based on the power capacities, while the bus size represents the magnitude of capacity installed in that region. Furthermore, it displays the existing and expanded transmission HVDC and HVAC transmission lines. The existing transmission infrastructure is shown in purple, while the capacity expansion of certain lines is shown in red.

In all cases we can see that wave energy has been a positive addition to the energy mix, but predominately as a shallow water devices. However, given the small contribution per country mix, the pie sector is not easily visible.

Solar and onshore wind dominated the deployed generating technologies installed extensively across Europe representing between 48-47% and 45-47% respectively of the overall generation mix across the different horizons. Total installed generating capacity grew from 2.37 TW in network 2030 to 2.72 TW in network 2050, following the increased electricity demand

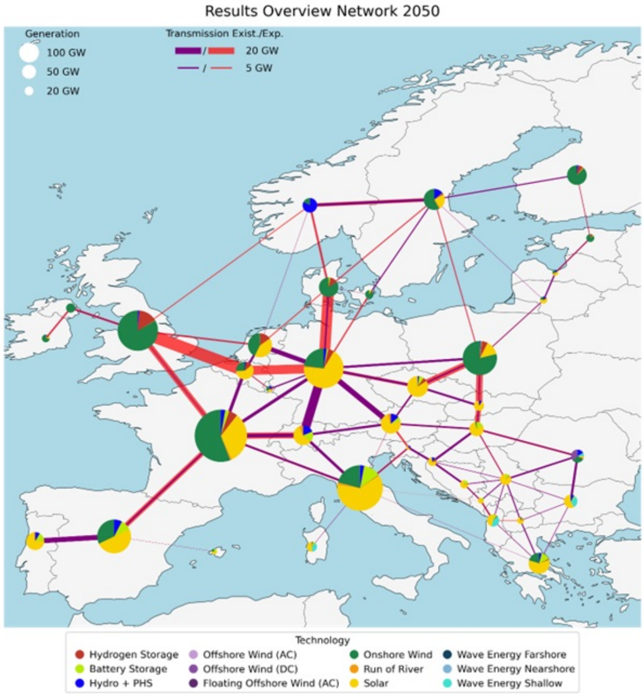

Fig. 6. Results Overview for network 2050

inputted exogenously. This was followed by existing hydroelectricity generation which was not optimized or extended with an aggregated fixed capacity of 99 GW. Wave energy shallow and offshore wind Direct Current(DC) where the two offshore technologies are most widely deployed. However, floating wind did not deploy as expected, due to higher costs, when compared to bottom fixed.

A. Power system behaviour

In general, from an overall system perspective, the model favours allocation of solar and onshore wind over other technologies due to them being more cost competitive. In fact, for some cases the model favours binary results, showcasing a fully onshore wind configuration for the UK and Denmark, or fully solar configurations in countries like Bosnia and Herzegovina and Serbia. The dominance of these technologies thus characterizes the overall system, since PyPSA is a cost-driven optimised. Deployment of the different storage technologies at diverse locations is correlated and can be explained, to a certain extent, by the deployment of these two mature renewable technologies (wind-solar).

In Figure 7 the relationship between generating and storage capacities. Figure 7a shows the strong correlation between aggregated generation capacity and aggregated storage capacity (R=0.92, R^2=0.84). Of course, electricity cannot be stored if it is not being generated, however, generation capacity of solar and wind seems to distinguish the type of storage technology and the amount of capacity installed at the same location.

Although the dominance of solar and wind is an interesting outcome of the future cost-optimal, it hides the issues for country grid stability and resilience/dependence. Such cost-driven systems can often times, require significant amounts of energy. As

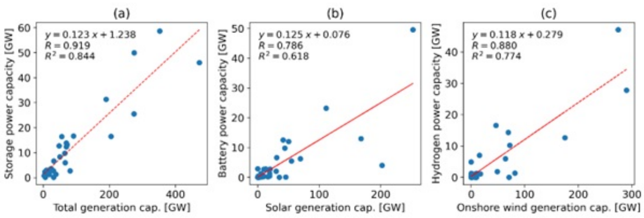

Fig. 7. Relationship between generation capacity and storage power capacity by country (a) Aggregated generation capacity vs. aggregated storage power capacity (all technologies) (b) Solar generation capacity vs. Battery storage power capacity (c) Onshore wind generation vs. Hydrogen storage power capacity.

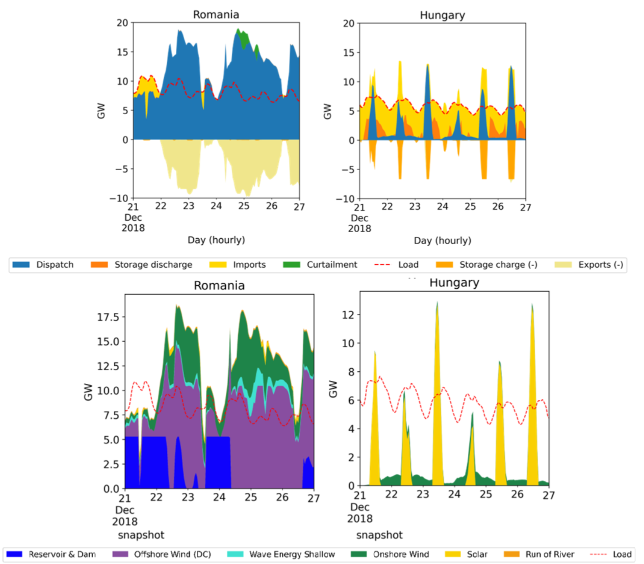

Fig. 8. System behaviour (top) time-series snapshot and Dispatched generation (bottom), December 21st to December 27th, Network 2050

an example, three countries with similar consumptions and vastly different energy mix characteristics are considered. Hungary has mostly solar, onshore and battery storage. Romania shows more diversity, with run-of-river, hydro, wave energy shallow, offshore wind, onshore wind, solar, with predominately battery and H_2, see Figure 8.

Romania's intermittent generation time series compared to Hungary are shown in Figure 8, particularly Hungary exhibits diurnal generation patterns determined by its mostly exclusive solar generation. In contrast Romania's hydro and offshore wind generation, seems to satisfy most of its electricity demand, while excess generation from the other technologies is mostly exported providing monetary gains.

Another discernable difference is how excess or insufficient power is balanced in each region. Romania, with only 129 MW of storage power capacity, exports most of its excess generation with some of it being curtailed. Hungary, is highly dependent on energy imports, not only to meet its electricity demand but also to store imported power to be used during the evening and at night (see Figure 8). Wave energy in particular seems to enable a smoother power output profile for Romania, and is dispatched to satisfy energy demand not only locally but elsewhere.

IV. Discussion & Conclusion

Solar PV, onshore wind and bottom fixed wind are the dominant technologies installed in the cost-optimal configurations, however, these are highly dependent on the additional costs allocated to offshore energies and in particular wave energy. The extra costs make the deployment of higher power dense farms less competitive, in a cost driven and free power flow system. These costs need to be refined for marine renewables and normalised them for the next iteration of PyPSA-MREL-TUD.

The climate data over-estimate the shallow water resources, skewing the potential for installation at shallower region. The large spatial discretization is unfavourable to nearshore devices, for which their area is constraint and not often are not considered. For farshore devices their production is under-estimate as the coarse data are under-estimating wave conditions for $H_{m0} \geq 6$m up to 10% and beyond that even further. The quality of wave data is of paramount importance both spatially and temporally, if the potential is to be assessed.

Although the results almost satisfy the 40 GW specific target of ocean energy in the EU Strategy on Offshore Renewable Energy, they fall extremely short of the overall target of 300 GW of offshore energy by 2050 with only 42.8 GW of aggregated offshore capacity by 2050. This can also be attributed to the fact that co-location (for now) was not supported and the coarse domain, did not evaluate the sitting of offshore renewables properly, as it gave priority to shallow WEC and bottom fixed. However, we do intent to mitigate the over-estimate in cost driven analysis for floating wind as well.

Marine renewables presence in the energy system, can reduce bigenerational patterns and decrease energy dependency and energy storage costs. Most energy system models currently have not taken into account marine renewables, and especially wave energy. Our PyPSA-MREL-TUD version fills the gap, but also unveils the limitations and next steps that need attention prior to a full comparative analysis. Cost driven models will be inherently biased by cheapest option, however, in the case of dynamic system like PyPSA, the temporal variability can be quantified positively or negatively. This element is a plus for wave energy, but its power production dependence on coarse data and the high range of uncertainties in costs reduce its efficacy in power production.

It is up to the wave energy sector to contribute to solutions and we hope that the PyPSA-MREL-TUD will fill the gap and unveil the untapped potential that wave energy has in the European Energy System.

Acknowledgement

We would like to thank and acknowledge the help of Dr Dalius Tarvydas from the Joint Research Centre (JRC) in the economic modelling of the PyPSA-MREL-TUD.

The work has been a part of the EU-SCORES project that has received funding from the European Union's

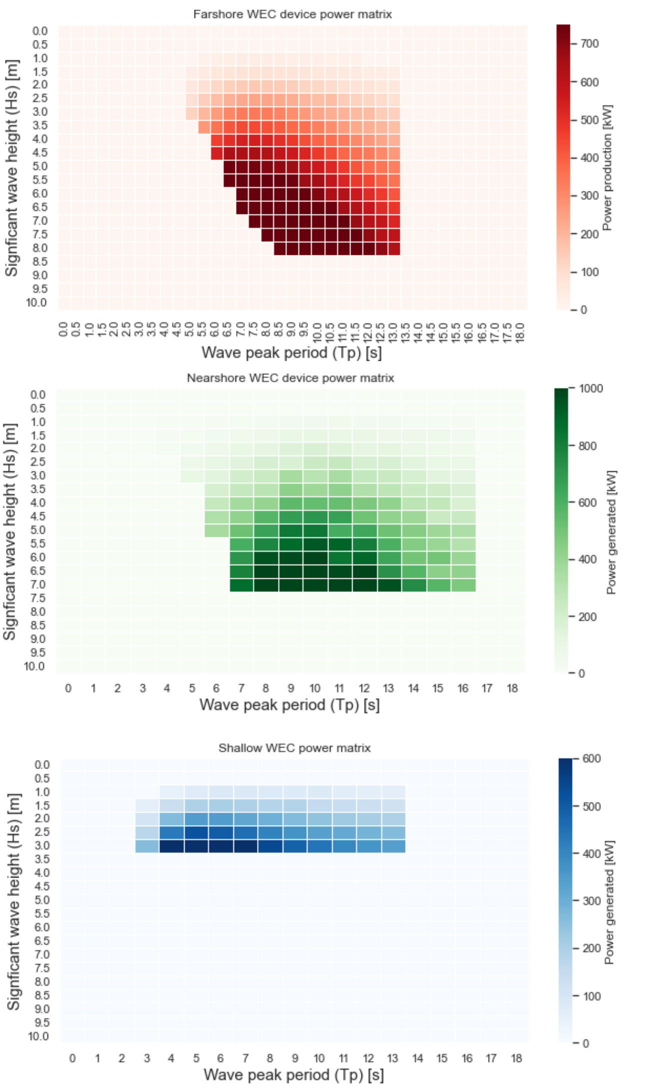

Fig. 9. Power Matrices integrated into this version of PyPSA-MRE-TUD

Horizon 2020 research and innovation programme under grant agreement No 101036457.

Appendix A
Power Matrices

References

[1] V. Masson-Delmotte, P. Zhai, A. Pirani, S. S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. Matthews, T. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, *Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021. [Online]. Available: http://www.ipcc.ch/report/sr15/

[2] U. Nations, "Adoption of the paris agreement," p. 32, 2015. [Online]. Available: http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[3] LAZARD, "Lazard's levelized cost of storage analysis-version 7.0," 2021. [Online]. Available: https://www.lazard.com/media/451882/lazards-levelized-cost-of-storage-version-70-vf.pdf

[4] S. Koohi-Fayegh and M. Rosen, "A review of energy storage types, applications and recent developments," *Journal of Energy Storage*, vol. 27, p. 101047, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352152X19306012

[5] J. Mitali, S. Dhinakaran, and A. Mohamad, "Energy storage systems: a review," *Energy Storage and Saving*, vol. 1, no. 3, pp. 166–216, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S277268352200022X

[6] U. E. A. Information, "Electricity storage technologies can be used for energy management and power quality." [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=4310#

[7] G. Lavidas, "Energy and socio-economic benefits from the development of wave energy in greece," *Renewable Energy*, vol. 132, pp. 1290–1300, 2019. [Online]. Available: https://doi.org/10.1016/j.renene.2018.09.007

[8] G. Lavidas and K. Blok, "Shifting wave energy perceptions: The case for wave energy converter (wec) feasibility at milder resources," *Renewable Energy*, vol. 170, pp. 1143–1155, 6 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0960148121002093

[9] S. Bhattacharya, S. Pennock, B. Robertson, S. Hanif, M. J. E. Alam, D. Bhatnagar, D. Preziuso, and R. O'Neil, "Timing value of marine renewable energy resources for potential grid applications," *Applied Energy*, vol. 299, p. 117281, 10 2021.

[10] M. Lehmann, F. Karimpour, C. A. Goudey, P. T. Jacobson, and M. R. Alam, "Ocean wave energy in the united states: Current status and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 1300–1313, 2016.

[11] G. Reikard, B. Robertson, B. Buckham, J.-R. Bidlot, and C. Hiles, "Simulating and forecasting ocean wave energy in western canada," *Ocean Engineering*, vol. 103, pp. 223–236, 2015. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0029801815001687

[12] IRENA, "Innovation outlook: Ocean energy technologies." [Online]. Available: https://www.irena.org/publications/2020/Dec/Innovation-Outlook-Ocean-Energy-Technologies

[13] T. Potapenko, J. S. Döhler, F. Francisco, G. Lavidas, and I. Temiz, "Renewable energy potential for micro-grid at hvide sande," *Sustainability 2023, Vol. 15, Page 2234*, vol. 15, p. 2234, 1 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/3/2234

[14] B. Rojas-Delgado, C. Ekweoba, G. Lavidas, and I. Temiz, "Ga-based permutation logic for grid integration of offshore multi-source renewable parks," *Machines 2022, Vol. 10, Page 1208*, vol. 10, p. 1208, 12 2022. [Online]. Available: https://www.mdpi.com/2075-1702/10/12/1208

[15] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system," *Energy*, vol. 160, pp. 720–739, 10 2018.

[16] D. P. Schlachtberger, T. Brown, M. Schäfer, S. Schramm, and M. Greiner, "Cost optimal scenarios of a future highly renewable european electricity system: Exploring the influence of weather data, cost parameters and policy constraints," *Energy*, vol. 163, pp. 100–114, 11 2018.

[17] N. Guillou, G. Lavidas, and G. Chapalain, "Wave energy resource assessment for exploitation-a review," *Journal of Marine Science and Engineering*, vol. 8, p. 705, 9 2020. [Online]. Available: www.mdpi.com/journal/jmse

[18] G. Lavidas, "Selection index for wave energy deployments (siwed): A near-deterministic index for wave energy converters," *Energy*, vol. 196, p. 117131, 4 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360544220302383

[19] A. F. D. O. Falcão, "Wave energy utilization: A review of the technologies," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 899–918, 4 2010. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1364032109002652

[20] G. Lavidas and V. Venugopal, "Application of numerical wave models at european coastlines : A review," *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 489–500, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.04.112

[21] M. Alday, F. Ardhuin, G. Dodet, and M. Accensi, "Accuracy of numerical wave model results: application to the atlantic coasts of europe," *Ocean Science*, vol. 18, no. 6, pp. 1665–1689, 2022. [Online]. Available: https://os.copernicus.org/articles/18/1665/2022/

[22] J. E. Stopa and K. F. Cheung, "Intercomparison of wind and wave data from the ecmwf reanalysis interim and the ncep climate forecast system reanalysis," *Ocean Modelling*, vol. 75, pp. 65–83, 3 2014. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1463500313002205

[23] G. Lavidas, V. Venugopal, and D. Friedrich, "Sensitivity of a numerical wave model on wind re-analysis datasets," *Dynamics of Atmospheres and Oceans*, vol. 77, pp. 1–16, 2017. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0377026516301154

[24] J. E. Stopa, "Wind forcing calibration and wave hindcast comparison using multiple reanalysis and merged satellite wind datasets," *Ocean Modelling*, vol. 127, pp. 55–69, 7 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1463500318301458

[25] G. Lavidas and H. Polinder, "North sea wave database (nswd) and the need for reliable resource data: A 38 year database for metocean and wave energy assessments," *Atmosphere*, vol. 10, pp. 1–27, 2019. [Online]. Available: https://www.mdpi.com/2073-4433/10/9/551/htm

[26] M. Alday, M. Accensi, F. Ardhuin, and G. Dodet, "A global wave parameter database for geophysical applications. part 3: Improved forcing and spectral resolution," *Ocean Modelling*, vol. 166, p. 101848, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1463500321001001

[27] F. Ardhuin, E. Rogers, A. V. Babanin, J.-F. Filipot, R. Magne, A. Roland, A. van der Westhuysen, P. Queffeulou, J.-M. Lefevre, L. Aouf, and F. Collard, "Semiempirical dissipation source functions for ocean waves. part i: Definition, calibration, and validation," *Journal of Physical Oceanography*, vol. 40, no. 9, 2010.

[28] M. Alday, H. Baki, G. Lavidas, and S. Basu, "Renewable coarse resource assessment for the european region (d6.2)." [Online]. Available: https://cordis.europa.eu/project/id/101036457/results

[29] D. Ingram, G. H. Smith, C. Ferriera, and H. Smith, "Protocols for the Equitable Assessment of Marine Energy Converters," Institute of Energy Systems, University of Edinburgh, School of Engineering, Tech. Rep., 2011. [Online]. Available: http://www.equimar.org/

[30] F. Delgado, G. Lavidas, and K. Blok, "Wave energy and the european transmission system," pp. 17–23, 10 2022. [Online]. Available: https://www.taylorfrancis.com/books/9781003360773/chapters/10.1201/9781003360773-3

[31] K. Blok and E. Nieuwlaar, *Introduction to Energy Analysis (third edition*. Routledge, 2020. [Online]. Available: https://www.routledge.com/Introduction-to-Energy-Analysis/Blok-Nieuwlaar/p/book/9780367434816

[32] E. Commission, "An eu strategy to harness the potential of offshore renewable energy for a climate neutral future," 2020. [Online]. Available: https://ec.europa.eu/energy/topics/renewable-energy/eu-strategy-offshore-renewable-energy_enhttps://ec.europa.eu/commission/presscorner/detail/en/ip_20_2096https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_2095https://eur-lex.europa.eu/leg

[33] E. Commission, D.-G. for Maritime Affairs, Fisheries, J. R. Centre, A. Addamo, A. Calvo Santos, J. Guillén, S. Neehus, A. Peralta Baptista, S. Quatrini, T. Telsnig, and G. Petrucco, *The EU blue economy report 2022*. Publications Office of the European Union, 2022.

[34] S. Bozzi, G. Besio, and G. Passoni, "Wave power technologies for the mediterranean offshore: Scaling and performance analysis," *Coastal Engineering*, vol. 136, pp. 130–146, 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0378383917304908