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Wave energy in Energy Systems, the impact of high-fidelity datasets and a view for the future.

George Lavidas, Lefteris Mezilis

Abstract—**Wave energy as a renewable resource has been shown to have immense potential. Up to date research has predominately focused on sector approaches, with devices being explored in small applications, or solely on their own merit. However, when discussing the integration to energy systems with high share of renewable energies, large levels of electrical interconnectivity and grid balancing infrastructure, the role of wave energy is often "lost". This work further refines the approach of integrating wave energy in the European and UK energy system, highlighting potential future pathways to improve wave energy considerations. This study assesses the input source of climate data for evaluation of wave energy production and economics. The comparison of ERA5 and a high-fidelity wave dataset across all Europe, the ECHOWAVE database, show a clear benefit for wave energy. When ERA5 is utilised to assess the potential of wave energy, the usefulness and integration of wave energy is not reflected in the system. This work shows that a proper representation of wave energy in terms of climate, power production methodologies and economic considerations.**

Index Terms—**Wave energy, system integration, energy modelling**

I. INTRODUCTION

ECONOMIC growth is 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 [1]. While at the short term, energy prices may slightly increase, in high renewable systems the wholesale price of electricity will be reduced, regardless of which variable renewable source is utilised. Of course, an optimal mixture is dependent on local resource utilisation, and high renewable energy penetration does not necessarily destabilise the grid [2].

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 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 pathways, providing insights on the necessary steps to decarbonise our energy systems.

In terms of wave energy in energy systems, one of the first studies to include wave energy was by Lund 2006 [3] 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, balancing variable wind and limited temporal solar production. Wave power generation was estimated using a 5% conversion efficiency on the wave energy flux. Following this uniquely targeted study, wave energy has not be assessed fully into working energy systems.

Wave energy installations also need to take into account the economic costs and create pathways for reduction. Lavidas et al [4] showed that milder resources are also viable for wave energy converters, and especially after proper resource-location matching the LCOE can reach 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. At a global Satymov et al [5] showed that wave energy can have a reduction path that would allow the Levelised Cost of Electricity (LCOE) for 2030 to be $\leq$ 100 €/MWh and $\leq$ 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 [6] had highlighted that a lot of studies use improper methods for wave power estimates, and often neglect to utilise proper resource and economic considerations. In the same study a first version of PyPSA-Eur-MREL was presented. In that work climate data ERA5, that are commonly used in the sector were model drivers. The results indicated that coarse data like ERA5 over-estimate the shallow water resources, skewing the potential for installation at shallower re-

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gion. The large spatial discretization is unfavourable to nearshore devices, for which their area is constraint and are not considered. For farshore devices, the coarser datasets *i.e.* ERA5 provide under-estimation in power production, as the $H_{m0} \geq$ 6m is persistently under-estimated 10%. It was suggested that the quality of wave data is of paramount importance both spatially and temporally, if the potential is to be assessed. This study contributes to knowledge by highlighting the impact that high resolution wave dataset have on the inclusion of wave generators into high renewable energy systems. For marine renewables, results underline the significance of datasets *i.e.* such as the ECHOWAVE, and should be the ones considered for the acceleration of wave energy as a viable option in energy systems.

A. Materials & Methods

This work builds upon past findings, improves and refines the approach to include all marine renewables into energy system models [6]. Hence, accelerating the considerations for wave energy integration and interaction of marine renewables into complex energy systems. The underlying PyPSA-Eur is an optimization model specific for the European power system at the transmission network level modelled on the Power System Analysis (PyPSA) toolbox [7], [8], 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 contribution of this work has lead to the development of PyPSA-Eur-MREL second version, with all marine renewables (wave and tidal). We present the significant impacts of wave data resolution on deployment potential, and finally the economic assumptions for wave energy are also re-thought for the sector.

The WEC functionality incorporated in PyPSA-Eur-MREL is subsequently coupled with metocean conditions, providing the capacity factor, and taking into account depth deployments of each raster cell. A packing density of $20-50MW/km^2$ was considered feasible by Lavidas et al 2021a,c [4], [9]. The extension for waves has considered for three different devices based on depth of deployment, with packing density for shallow $30MW/km^2$, nearshore $35MW/km^2$ and farshore $50MW/km^2$. The WECs represent the sector's most widely utilized devices. The WECs considered include a point absorber whose geometry is inspired by the Corpower C4 WEC (point absorber-nearshore), Mocean (attenuator-farshore), and a flap type (Waveroller terminator-shallow). The power matrices for all the devices were developed by Marine Renewable Energies Lab (MREL) at Delft University of Technology, see Figure 1.

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. The power matrices based on sub-optimal power-take-off modelled with a weakly non-linear model, utilizing the open-source BEM solver HAMS-MREL [10]. The power matrix is constructed considering irregular sea states based on the JONSWAP spectrum for the power calculation. WECs represented are noted as shallow (0-20m depth), nearshore (20-80m depth), farshore (50-150m depth). This means that for the WECs, once the build profile are generated for each node the optimal WEC selected is based on lowest Levelised Cost of Electricity (LCOE).

Attention was paid to use the most optimal

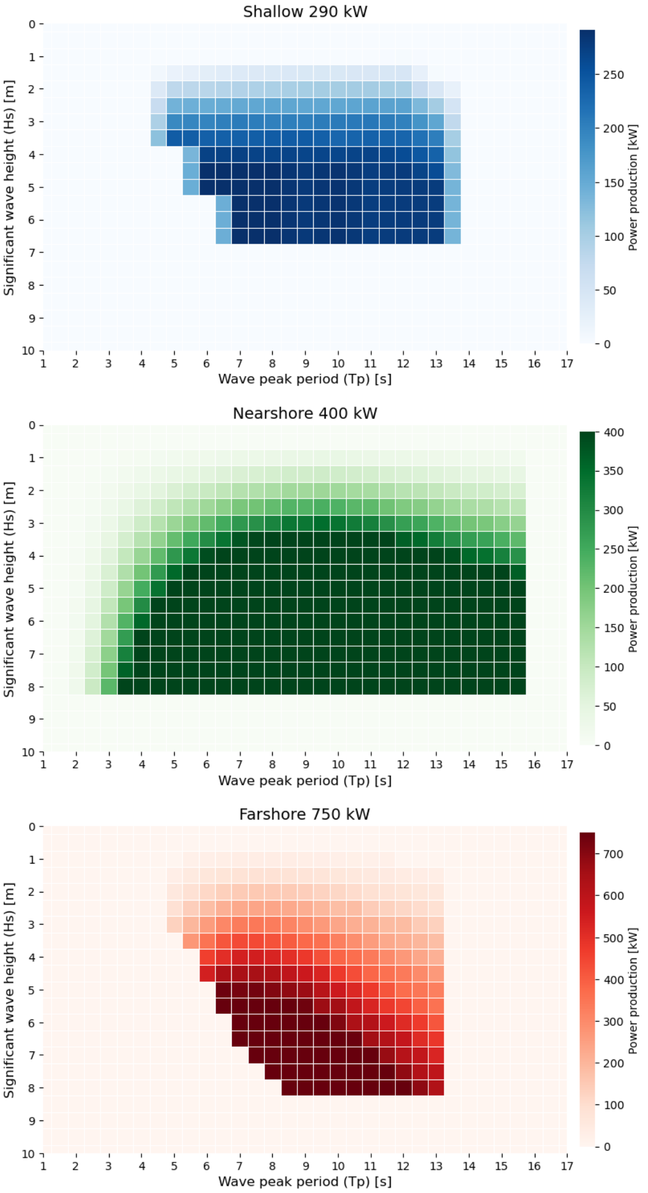

Fig. 1. Power matrices for WECs used in PyPSA-Eur-MREL, shallow is a terminator, nearshore is a point absorber, and farshore is a hinged attenuator.

and proper wave conditions. For this reason the ECHOWAVE dataset was developed, that represent a state-of-the-art wave spectral database. ECHOWAVE mitigates the issues that coarser re-analysis dataset, with large under-estimations. While they are a useful source to draw an initial mapping of resources, there are several important limitations of these data sources. Probably most obvious limitation, is the spatial resolution of global models, typically ranging from 0.5^o to 0.25^o, which is equivalent to $\approx$ 55 km to $\approx$ 27 km [11], [12]. Comparison of ERA5 wave date with along-track satellite data and the ECHOWAVE dataset, reveals that the performance of ERA5 degrades as the wave heights increase [13]. Estimating wave energy production with ERA5 leads to significant under-estimations in power production, with recorded under-estimating differences $\approx$ 25-30% [14].

The ECHOWAVE 30-years hindcast provides spatial resolution of (~ 4 km) and temporal (1 hr) resolution wave fields and spectral data within the European coastal shelf. One of the main characteristics of this dataset is the use of TUD-165 parameterisation and wind intensities correction proposed by Alday & Lavidas [13]. 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 parametrisation were extensively verified (and then validated) with measurements from the ESA Sea State CCI V3 altimeter product [15]. For tidal resource we added constituents and velocities from the reanalysis of North-West European Shelf with a 7 Km resolution. The ocean model is NEMO (Nucleus for European Modelling of the Ocean) [16].

The European Energy grid has been modelled with 130 nodes for 2030, using a greenfield approach to investigate impacts of the 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. Case 1 is considered the base/benchmark, using coarse ERA5 dataset for all resource, Case 2 uses the high resolution ECHOWAVE based on the year 2020.

II. MARINE RENEWABLE ECONOMICS

As the PyPSA-Eur-MREL model was being developed, a very sensitive behaviour was noticed with regards to cost modelling assumptions [6], [17]. Given the plethora of options in the 100% renewable energy system, the marine costs sensitivity are highly influential. Therefore, to realistically consider the 2030 future horizon, we have adapted all technological costs via learning curves and external cost databases, in particular the European Union EU Reference Scenario [18].

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. Technological learning is modelled through the one variable factor-learning curve approach [19], [20]. 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 for most marine renewables a learning rate was used to estimate the potential cost reductions more realistically. A learning rate of 15% is used between 2020 and 2030, this was estimated in order to reach the minimum required capacity of 1 GW target of the Offshore energy strategy.

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. Estimation of WEC initial costs a variable rate per type has been considered, with the farshore device has a cost of 5,000 €/kW, nearshore 4,000 million €/kW, and shallow 3,000 €/kW [21]–[24].

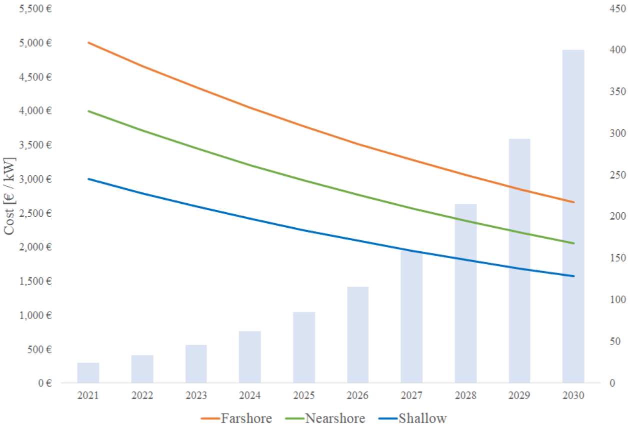

Fig. 2. Application of the variable learning rate for WEC deployments, the three different devices (farshore, nearshore, shallow) are modelled. The first y-axis shows the CAPEX per WEC, and the second are cumulative achieved deployments

III. RESULTS

First 2030 run is the benchmark coarse dataset of ERA5 that allows to explore the performance of wave energy integration. Most Northern countries have predominately onshore and bottom fixed wind, with total installed capacity $\approx$ 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 $\approx$ 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 $\approx$ 87 GW (see Figure 3). Also for the first time, wave energy is also considered with 6 GW installed in Spain, utilizing the nearshore WEC, see Figure 3. 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 $\approx$ 104 TWh.

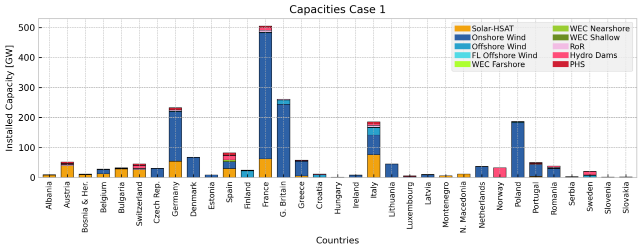

Fig. 3. Installed capacity and percentage for each generator category per country for 2030, with the model driven by coarse data (ERA5)

Case 2 (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), see also Figure 5. 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 Figure 4.

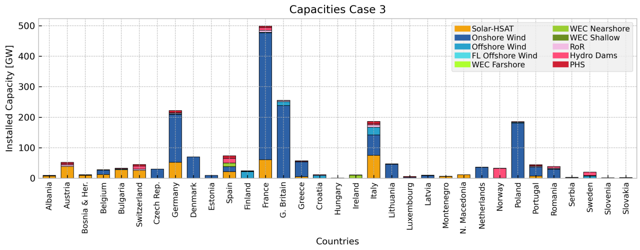

Fig. 4. Installed capacity and percentage for each generator category per country for 2030, with the model driven by high resolution data (ECHOWAVE).

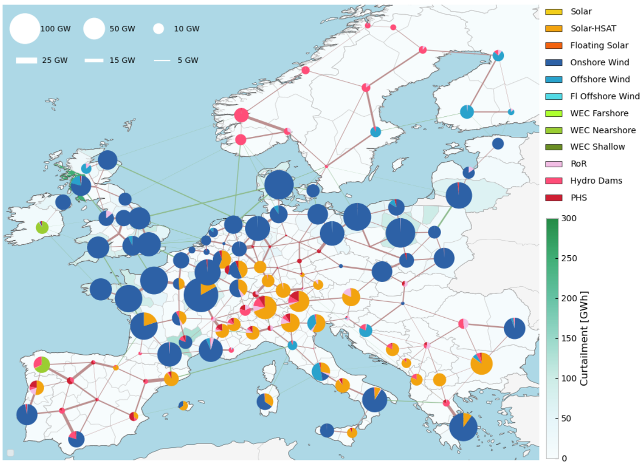

Fig. 5. European and UK grid 2030 representation with ECHOWAVE dataset, including the expansion lines necessary to achieve 100% renewable energy generation

TABLE I
INSTALLED CAPACITIES PER GENERATORS AND STORAGE MEDIUMS FOR ALL CASES

	Installed Capacity (GW)	
	Case 1	Case 3
Floating Wind	-	-
Floating Solar	-	-
Offshore Wind	88	88
Onshore Wind	1,441	1,400
Solar	0	0
Solar-HSAT	371	362
Wave Farshore	-	-
Wave Nearshore	6	22
Wave Shallow	-	-
H_2 electrolysis	25	24
H_2 fuel cell	93	94
Batteries	92	91

Figure 5 showcases both the spatial and generator capacity of the Case 2. Due to the lack of good climate information for wind, energy storage is needed, as wind is considered a ”base” load generator. Installed capacities of H_2 of 94 GW are almost identical with Case 1, and battery storage also has similar capacity with 91 GW. The overall energy system approach for both cases are presented in Table I.

IV. CONCLUSIONS & DISCUSSION

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 dataset. A higher temporal resolution allows the generators to capture regional variabilities in intensity.

Energy systems driven by coarse climate data ($\geq$ 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 commercialized, the usage of a high resolution dataset drives installations of wave energy converters up to 22 GW.

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.

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, and than 5 Km for wave energy.

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