EVOLVE
Place, Time and Value study
for Blue Energy across Europe

The system benefits of ocean energy to European power systems

Technical note: EVOLVE country-scale modelling study

Produced by the EVOLVE Consortium

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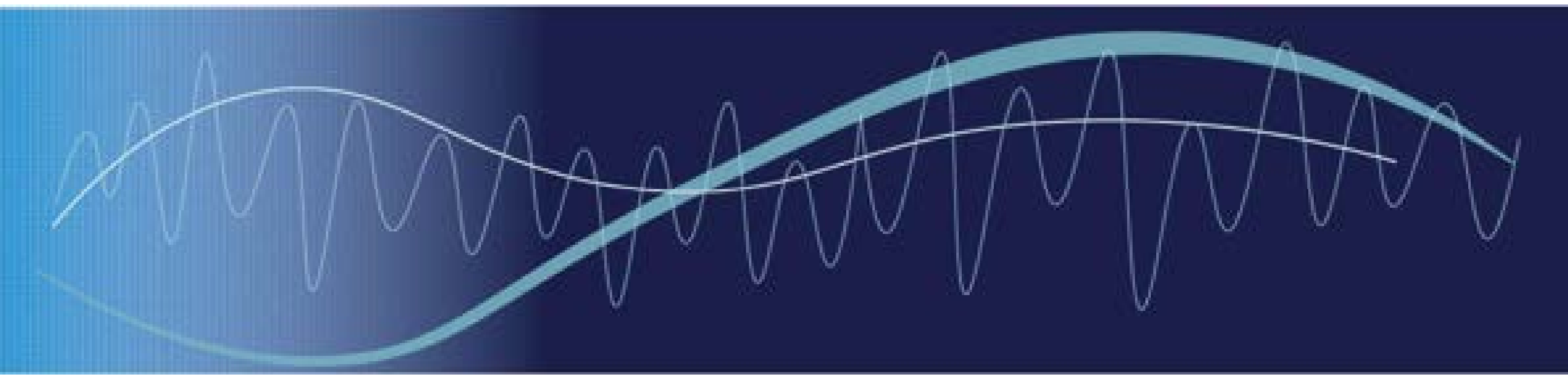


SUMMARY - THE SYSTEM BENEFITS OF OCEAN ENERGY TO EUROPEAN POWER SYSTEMS

This technical note details the country-scale power system modelling analysis performed through the OCEANERA-NET EVOLVE project. The project aims to develop an understanding of the system benefits of ocean energy within future high-renewable power systems, using the analysis of production, supply and demand profiles and credible future energy supply scenarios. It has been postulated that since wave and tidal availability is offset from other renewables such as wind and solar PV, it could be of benefit to system operation to include a more diverse mix of renewables which includes ocean energy.

To test this theory, economic dispatch models have been built representing three regions: Great Britain, Ireland, and Portugal, at three different points in time: using established future energy scenarios for 2030, 2040, and 2050. The proportion of wave and/or tidal stream generation within each scenario has been varied, whilst keeping the total available renewable energy constant, to quantify any potential system benefits purely from the inclusion of ocean energy within the generation mix.

Stakeholder engagement has been undertaken throughout the modelling process, taking the form of internal consortium workshops, one-to-one interviews, and regional workshops. Overall, 70 external stakeholders were engaged with throughout the EVOLVE project, over 33 organisations. The stakeholder engagement process provided very useful feedback to refine the system benefits modelling methodology and results analysis.

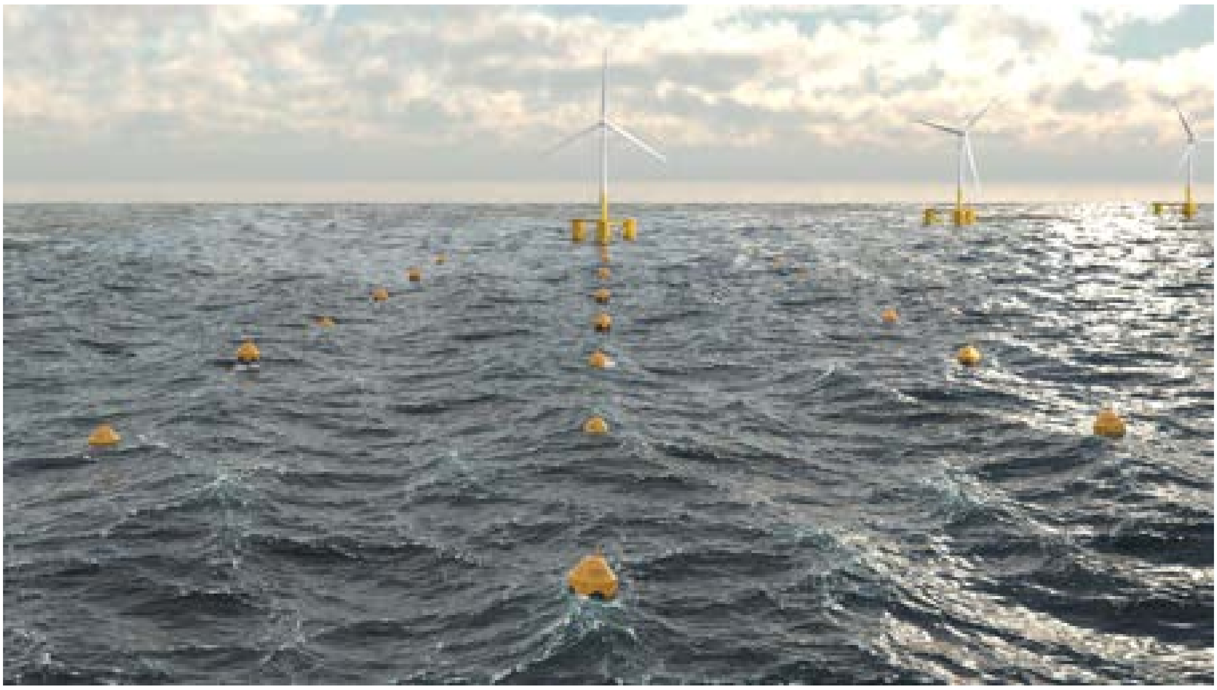
It has been found that including ocean energy (both wave and tidal stream) within future European energy mixes consistently produces system benefits over all scenarios studied for all three regions.

These system benefits can be quantified over a range of metrics: increased renewable dispatch; decreased fossil fuel dispatch; decreased curtailment volumes; decreased dispatch costs; decreased carbon emissions; decreased price volatility; and increased price capture for ocean energy technologies. For example, the cost reduction results in this technical note range from £90M (1GW of wave in GB in 2030) to £1.46bn (10GW of wave in GB in 2040) and the carbon reduction results in this report range from 10 $ktCO_2$ (1GW of tidal stream in GB in 2040) to 1.06 $MtCO_2$ (10GW of wave in GB in 2030). Ocean energy is also able to capture up to 2.2× the wholesale price of wind (1GW of wave in GB in 2050).

It has been found that these system benefits vary between the different regions and years modelled. While some metrics increase with increasing rates of decarbonisation (e.g. cost and curtailment reduction), others increase in the higher carbon scenarios (e.g. fossil fuel and carbon reduction). **The key result is that including a higher proportion of ocean energy within our future electricity mixes consistently results in higher renewable dispatch**, for the same total renewable energy availability, due to the offsetting of wave and tidal with wind and solar generation. The ability to dispatch more renewables results in lower fossil fuel and peaking plant dispatch, and thus lower total dispatch costs and carbon emissions.

This analysis is particularly meaningful as there are very few studies that quantify the system benefits associated with including ocean energy within country-scale power systems, and no studies that do so over quite so many metrics. These results will be of interest to various stakeholders across the sector: technology and project developers, academic and industrial researchers, and grid operators and policy makers looking to develop future decarbonised systems whilst maintaining security of supply.

CONTENTS



Simulated combined wind and wave farm (Image courtesy of CorPower Ocean AB)

1 INTRODUCTION

The EVOLVE project is funded through the OCEANERA-NET Cofund, with project partners from Scotland, Sweden and Portugal. The key objective of the EVOLVE project is to analyse the overall market value of including ocean energy in the European energy mix; ocean energy here being defined as tidal stream and wave energy. The project has focused on three European regions of interest: Great Britain (GB), Ireland (IE) and Portugal (PT).

Three key studies have been undertaken throughout the EVOLVE project, examining:

- The practical deployment potential for wave and tidal stream technologies in the EVOLVE regions of interest;
- The quantifiable system benefits (in terms of economics, carbon reduction and power system operation) of wave and tidal stream deployments in the EVOLVE regions of interest and;
- The potential role of wave and tidal stream within 100% renewable islanded systems, utilising the Orkney Islands, Scotland, as a case study.

This technical note summarises the second of these studies: running dispatch models representing the power systems of the three regions of interest to compute the least-cost supply-demand balance, and quantify the impact that wave and/or tidal generation can have on these generation dispatch results.

It has been found that wave and tidal availability is often offset from other renewables, such as wind and solar PV [1], [2]. Therefore, it could be of benefit to power system operation to include a more diverse mix of renewables which includes marine energy. Resource offsetting between marine energy and other variable renewables are shown in terms of seasonal trends for Great Britain (GB) in Figure 1. It can be seen that electricity demand is highly seasonal in GB, with higher demand in the winter months. Wind generation also has a seasonal profile, with higher peaks in winter. Solar generation, conversely, is higher in the summer months.

It can also be seen that tidal energy is more consistently available throughout the year than any other form of variable generation. It has no correlation to other variable renewables, and so can be available at times of low wind or solar resource. Wave energy, however, is highly seasonal, with much higher resource in the winter months. This means that wave energy availability correlates well with the GB demand profile. It is offset from other variable renewables, and can be available at times of low wind or solar resource.

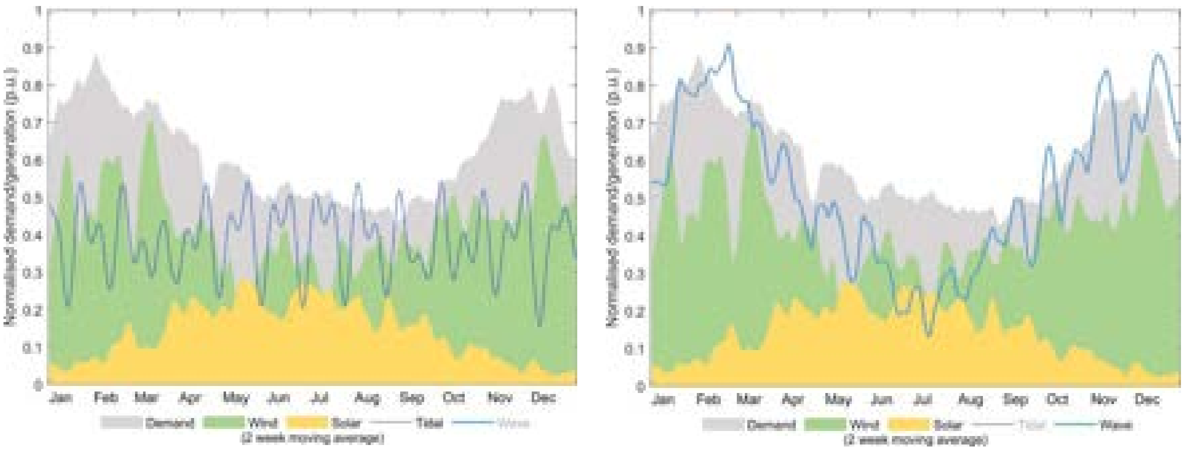


Figure 1. Normalised demand and variable renewable generation for GB, based on 2019 weather data, compared with tidal stream (left) and wave (right) variable renewable resource.

This study involves gaining an understanding of the market value of ocean within a future power system with a high penetration of other forms of renewables using the analysis of production, supply and demand profiles and credible economic energy supply scenarios. This modelling considers three case studies, covering the electricity grids of Great Britain (GB), Ireland (IE), and Portugal (PT). Note that the GB grid covers England, Wales, and Scotland; whilst the IE grid covers Northern Ireland and the Republic of Ireland (Éire).

The work presented in this technical note has the following aims:

- Develop custom-built economic dispatch models representing three European regions (Great Britain, Ireland, and Portugal) and three future years of interest (2030, 2040, 2050).
- Evaluate how varying penetrations of wave and tidal generation capacity impact on the economics and security of supply of large-scale power systems.
- Compare the system benefits results between regions, and discuss the limitations associated with the modelling methods and inputs.

The expertise of the EVOLVE consortium is particularly well suited to this, as modelling experts at the University of Edinburgh and Research Institutes of Sweden have years of experience working with energy systems models. The consortium also contains the expertise of an active wave technology developer (CorPower Ocean) and an active tidal stream technology developer (Orbital Marine Power). Figure 2 illustrates these wave and tidal technologies.

Figure 2. Ocean energy devices: CorPower Ocean's point-absorber WEC (left) and Orbital Marine Power's floating tidal device (right).

2 METHOD

The methodology developed for this study follows four stages, illustrated below. Stakeholder engagement has taken place throughout the EVOLVE project, providing feedback at each of these stages.

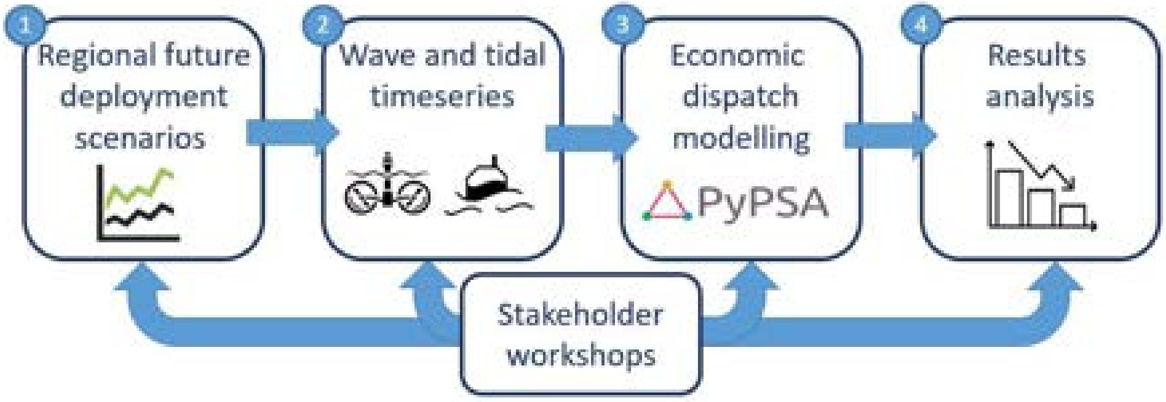


Figure 3. Overview of methodology stages

Stage 1: Regional future deployment scenarios
Future projections of the regional electricity systems in key years were collected for each region, using historical data from 2019 and future projected energy scenarios. These are consistent with official roadmaps of future energy supply and use, aimed towards the goal of net-zero carbon emissions by 2050. The projections consider electricity demand together with capacity of various generation and storage technologies**.**

For Great Britain, the 2021 Future Energy Scenarios (FES) published by National Grid ESO [3] have been used as the basis of future supply and demand projections. For Ireland, both EirGrid (grid operator for Ireland) and SONI (electricity transmission system operator for Northern Ireland) produce 'Tomorrow's Energy Scenarios' with projections for future electricity demand and generation on the respective part of the Irish Grid [4, 5]. Finally, for Portugal the 2020 Energy Scenarios in support of the Portuguese Strategy for Hydrogen (EN-H2) [6] were used to provide future supply and demand projections.

Stage 2: Wave and tidal time series creation
Hourly availability profiles were derived representing variable renewable generation: wind, solar, wave and tidal stream. These availability profiles are a key input to the economic dispatch model, which is constrained to ensure that the dispatched variable renewable generation does not exceed the variable renewable availability. Renewable resource data within this modelling is generated using 2019 as a base year, which is consistent with the demand base year. This ensures that the cross-correlations between renewable generation sources, and with demand, are maintained.

Offshore wind, onshore wind and solar generation time series have been generated using the Renewables.ninja tool [7]. This software takes solar irradiance and wind speed data from NASA's MERRA reanalysis [8] and applies a Virtual Wind Farm model [9] and a Global Solar Energy Estimator model [10] respectively to generate hourly wind and solar generation time series for the specified coordinates.

Wave energy time series have been derived using hourly wave resource data (significant wave height and peak wave period) utilising hindcast data from Copernicus marine services [11]. Suitable wave sites for each region were first screened using PacIOOS' WaveWatch III (WW3) model [12], and then hourly resource data generated using Copernicus ARTIC_MULTIYEAR_WAV_002_013 [13] (for GB north) and IBI_MULTIYEAR_WAV_005_006 [14] (for GB south, Ireland and Portugal). The hourly wave resource time series data is then converted to hourly generation time series using CorPower Ocean's G12 power matrix – intended to represent a typical wave energy converter in the future scenarios modelled.

Analysis of tidal stream has been included for the GB system only, due to much lower tidal resource in both Ireland and Portugal compared with Great Britain. Tidal stream time series for GB have been created based on hydrodynamic modelling of tidal stream resource at the University of Edinburgh, and tidal stream energy generation modelling at the University of Plymouth [2]. Regional coastal ocean flow models were configured in the Thetis coastal ocean model [15], to simulate the variability in the tidal dream resource at sites of interest. Velocity magnitude predictions are exported at 100s intervals over a simulation period of 3 months. The data was extrapolated using harmonic analysis [16] to obtain the 2019 annual data set for each site.

Stage 3: Economic dispatch modelling

Economic dispatch models have been developed which represent the current and future electricity grids of Great Britain (GB), Ireland (IE), and Portugal (PT). Python for Power Systems Analysis (PyPSA) [17] software is used to compute hourly optimal dispatch for each power system, minimising the total cost of dispatch whilst maintaining supply-demand matching on an hourly basis. This represents a perfectly competitive wholesale market, where generation bids based on short-term (fuel and carbon) costs, and the market clears at the price of the marginal generator in every hourly timestep.

PyPSA v0.19.1 was used to develop the regional models. PyPSA is a partial equilibrium model that optimises the short-term operation of the energy system as a linear problem using the linear optimal power flow equations. More information can be found within the PyPSA documentation [18].

Generator marginal costs are input to the model based on projected fuel and carbon costs, sourced from the 2020 BEIS Electricity Generation Costs Report [19]. Fuel-based electricity generation (fossil fuels, nuclear, biomass, hydrogen, energy from waste) are all assumed to have a marginal cost equal to their fuel cost, with carbon costs included for fossil fuel generation. Variable renewable generation (wind, solar, wave, and tidal stream) are all assumed to have a marginal cost of zero, taking the hourly wholesale marginal price set by fuel-based electricity generation sources. This means that the dispatch models cost-minimising objective function will prioritise low-cost renewable generation within the merit order, and dispatch renewable energy first before more expensive generation sources.

Stage 4: Results analysis

As a key element of the EVOLVE project, a sensitivity analysis including ocean energy within the overall electricity generation mix was then performed. This involved substituting ocean energy (wave and/or tidal stream) for some of the additional offshore wind generation capacity expected to be in the electricity mix in future years. To facilitate fair comparison between technologies with different capacity factors, the total annual renewable energy generation availability was kept constant.

A range of output metrics were investigated, including economic metrics such as wholesale market prices, and environmental metrics such as carbon emissions. Comparison of these metrics between scenarios with and without ocean energy was used to demonstrate the overall system benefits possible from installing ocean energy as part of the future European energy mix.

3 RESULTS

3.1 GREAT BRITAIN

The power system of Great Britain is pictured to the right, with HVDC lines shown in purple, highlighting the interconnection with Ireland and Europe, as well as internally within GB. The Outer Hebrides and Orkney are both linked to mainland Scotland by 33kV undersea cables (not shown), with an HVDC link to Shetland under construction. The current GB system has around 24GW of wind and 13GW of solar installed, with these renewables making up close to 40% of the total installed capacity in GB [2].

Figure 4. Schematic of GB grid [27]

The GB power system falls under the United Kingdom political target for a net-zero energy system by 2050 [20], with aims for a net-zero electricity system by 2035 [21]. Further to this, the British Energy Security Strategy released in 2022 states ambitious targets for wind, new nuclear, solar and hydrogen in the coming years, to reduce reliance on oil and gas imports [22]. This includes the ambition of up to 24GW of new nuclear by 2050, 10GW of hydrogen production capacity by 2030, and 50GW of offshore wind by 2030, 5GW of which from floating offshore wind.

The 'Leading the Way' 2021 Future Energy Scenario (FES) published by National Grid ESO [3] has been used as the basis of future supply and demand projections. This scenario is very high renewable, describing the fastest possible decarbonisation journey for Great Britain, through a combination of high consumer engagement and world-leading technology and investment. In this scenario GB reaches net zero before 2050.

It can be seen in Figure 5 that the deployment trajectory of the Leading the Way scenario rapidly increases between 2020 and 2050, with renewable energy like wind and solar making up the highest proportion of new installed capacity in the coming decades. Fossil fuel installed capacity steadily decreases between 2020 and 2040, and both hydrogen and energy storage installed capacity rise significantly from 2030 onwards.

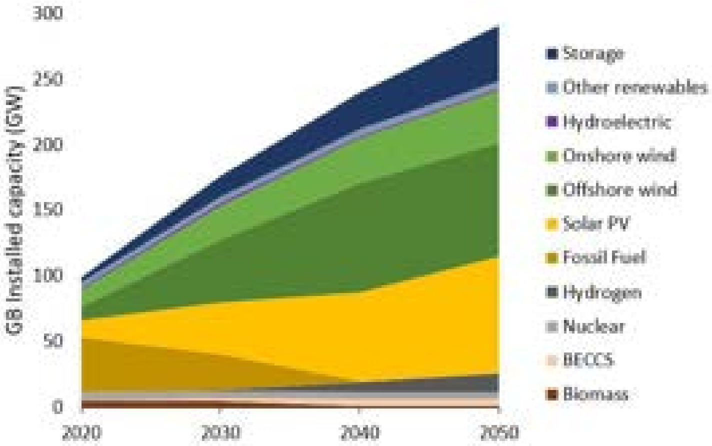


Figure 5. Installed capacity trajectory for Great Britain between 2020 – 2050, from the FES Leading the Way Scenario [3]

Table 1 shows the dispatch, cost, and carbon results for the 2030 LTW scenario, comparing the baseline case with no ocean energy with a case that switches 1GW of tidal stream with the equivalent energy output of offshore wind and a case that switches 1GW of wave in the same manner. It can be seen over the nine metrics explored, that the wave and tidal cases show increased performance when compared with the baseline case which does not include ocean energy. For example, including 1GW of wave or tidal allows for more renewable energy to be dispatched, thus less energy needs to be curtailed and less fossil fuels required to be dispatched. It should be noted that 1GW of installed capacity makes up approximately 0.5% of the total ~170GW of generation, and so although the results show only a small difference between the baseline case and wave and tidal cases, these impacts are in line with the change in ocean energy installed capacity.

Including wave or tidal energy also decreases the total cost of dispatch, the average marginal price of dispatch and the resultant carbon emissions from generation dispatch. These metrics quantify the potential annual cost savings to the consumer from 1GW of ocean energy as £100M for tidal and £90M for wave.

Table 1. System benefits from including 1GW of wave or tidal within the GB 2030 energy mix, over nine metrics.

Metric	Baseline case (0GW ocean)	Tidal sensitivity (1GW)	Wave sensitivity (1GW)
Renewable dispatch (TWh)	290.73	291.10 (+0.13%)	290.94 (+0.07%)
Proportion renewable dispatch (%)	82.41%	82.51% (+0.12%)	82.49% (+0.10%)
Curtailed renewables (TWh)	22.86	22.45 (-1.79%)	22.57 (-1.27%)
Proportion of renewables curtailed (%)	7.77%	7.63% (-1.80%)	7.67% (-1.29%)
Fossil fuel dispatch (TWh)	10.62	10.39 (-2.17%)	10.31 (-2.92%)
Proportion fossil fuel dispatch (%)	3.01%	2.95% (-1.99%)	2.92% (-2.99%)
Average marginal price (£/MWh)	37.30	37.01 (-0.78%)	37.06 (-0.64%)
Total cost of dispatch (£bn)	13.16	13.06 (-0.76%)	13.07 (-0.68%)
Carbon emissions ($MTCO_2$)	3.86	3.78 (-2.07%)	3.74 (-3.11%)

Figure 6 shows the resultant reduction in annual dispatch costs and carbon emissions when the renewable energy mix is adjusted to include higher proportion of wave or tidal generation, up to 10GW in all scenarios. It can be seen that this trend of cost and carbon reduction from including ocean energy continues with increasing penetration within the renewable mix.

We see a higher impact on costs in higher renewable scenarios, with up to £1.46bn cost reduction after 10GW wave and £1.35bn cost reduction after 10GW of tidal in the 2040 scenario, and £1.23bn from 10GW wave and £900M from 10GW tidal in the 2050 scenario. These scenarios have higher proportions of renewables and the offsetting from wave and tidal can thus have a bigger impact. The 2040 scenario produces the highest cost reduction results, as it has the tightest supply-demand margins. This is because by 2040, fossil fuels have been almost entirely replaced by low carbon renewable energy sources, but more flexible low carbon generation such as hydrogen and battery storage are not yet deployed at large scale (see Figure 5). It is interesting to note that in the 2030 scenarios we see the cost reduction trajectory begin to flatten out for wave energy after 8GW deployed and for tidal stream after 6GW deployed. When compared with the 2040 and 2050 scenario results this emphasizes that high installed capacities of ocean energy will have most impact in reducing system costs in more heavily decarbonised, high renewable scenarios.

Conversely, there is a higher impact on carbon reduction in the lower renewable near term scenarios, with 1.06 $MtCO_2$ reduction from 10GW wave and 700 $ktCO_2$ reduction from 10GW tidal in the 2030 scenario. This year contains the highest deployment of fossil fuels and as such has the most potential for emissions displacement. By 2050, the energy mix has met the net zero target, and so there is no change in carbon emissions from including ocean energy as there are zero total carbon emissions in any 2050 model run.

These results highlight the continued opportunity for cost and carbon reduction from including ocean energy within future energy mixes. In particular, they signify the high potential for carbon reduction from near-term deployments of ocean energy and high potential for cost reduction for longer-term deployments within high renewable scenarios.

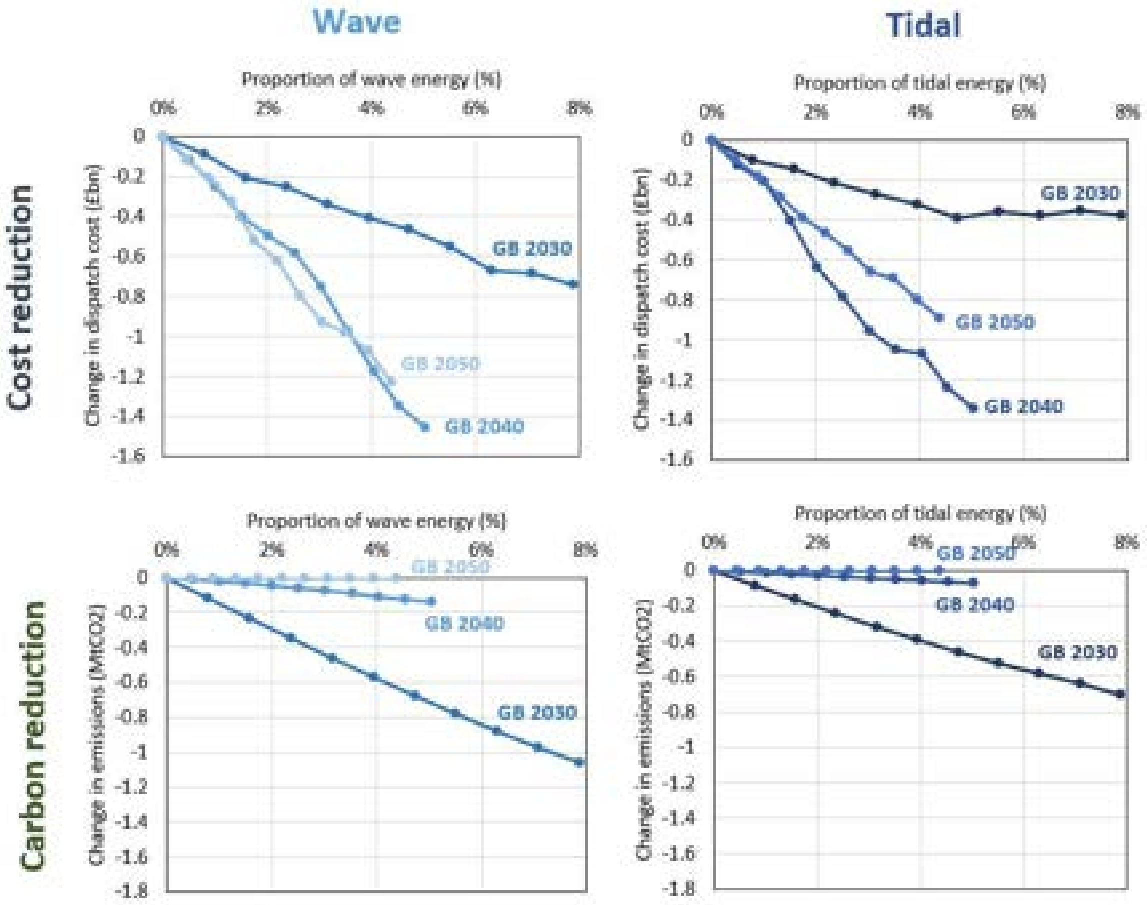


Figure 6. Cost and carbon reduction results for GB future scenarios when adjusting the proportion of wave or tidal energy within the renewable mix. Each data point is from a separate model run, where the installed capacity of wave or tidal is increased in 1GW increments up to 10GW.

Finally, Table 2 shows the price capture of variable renewables in the base case and ocean energy cases in the 2030 scenario. Both wave and tidal generation are able to capture higher wholesale prices than wind and solar, up to 58% higher for tidal and 59% higher for wave. This is because ocean energy generation profiles can be available at times of low wind and solar resource, and with a relatively low penetration of wave or tidal energy in the system it is likely that they will take the marginal price set by a more expensive generator at times of low wind and solar resource. This trend for higher price capture also continues within the 2040 and 2050 scenarios, with up to 2.2x higher price capture for ocean energy technologies in 2050 compared with wind and solar.

Table 2. Price capture results – 2030 GB scenario

Metric	Baseline case (0GW ocean)	Tidal sensitivity (1GW)	Wave sensitivity (1GW)
Solar price capture (£/MWh)	22.97	22.44	22.78
Offshore wind price capture (£/MWh)	26.08	25.95	25.90
Onshore wind price capture (£/MWh)	25.04	24.86	24.80
Wave price capture (£/MWh)	—	—	38.40
Tidal stream price capture (£/MWh)	—	38.57	—

3.2 IRELAND

The current Irish electricity system is dominated by fossil fuels (54% of installed capacity) and onshore wind (40% of installed capacity). Similarly to GB, Ireland has a political target for net zero emissions by 2050 [23]. This is supported by an interim target to reduce emissions by 51% by 2030, compared with 1990 levels, and sectoral emissions ceilings [24].

Both EirGrid (grid operator for Ireland) and SONI (electricity transmission system operator for Northern Ireland) produce 'Tomorrow's Energy Scenarios' with projections for future electricity demand on the respective part of the Irish Grid [4, 5].

Figure 7. Schematic of Irish grid [27]

The Irish scenarios developed for this analysis are based on the combination of 'Addressing Climate Change' (ACC) and 'Centralised Energy' (CE) scenarios from SONI and Eirgrid, respectively. Both of these scenarios are highly electrified and renewable, resulting in a low carbon future for Ireland as it moves towards a net zero target for 2050.

It can be seen from Figure 8 that the installed capacity of renewables, and particularly onshore wind, increases considerably between 2020 and 2040 in the Irish scenario. Fossil fuel installed capacity decreases from 2020 onwards, and other renewables such as solar PV and offshore wind are brought in to meet demand. Storage also increases significantly from 2020 onwards.

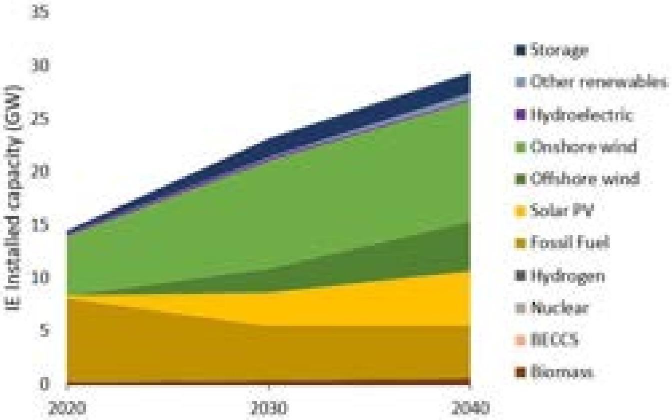


Figure 8. Installed capacity trajectory for Ireland between 2030 – 2040, from ACC and CE scenarios [5], [4].

As with the GB results, it can be seen over the nine metrics explored, that the wave cases show increased performance when compared with the baseline case which does not include ocean energy, shown in Table 3. The results indicate that when including 1GW of wave energy within the Irish 2030 energy mix, the renewable dispatch and the proportion of renewables dispatched increase, compared to the baseline case with no wave energy. Some other metrics are found to decrease, including curtailed renewables, fossil fuel dispatch, average marginal price, dispatch cost and carbon emissions. These metrics quantify the potential annual cost savings to the consumer from 1GW of wave energy as €272M.

Figure 9 shows the reduction in annual dispatch costs and carbon emissions when the proportion of wave energy increases within the Irish renewable energy mix, up to 3GW. This trend of cost and carbon reduction from including ocean energy continues with increasing penetration within the renewable mix. In this case, the cost and carbon reduction are both higher for the 2040 scenario, by up to €0.8bn and 1.6MtCO2 from 3GW of wave energy in Ireland in 2040.

Table 3. System benefits from including 1GW of wave within the Irish 2030 energy mix, over nine metrics.

Metric	Baseline case	Wave sensitivity (1GW)	% difference
Renewable dispatch (TWh)	31.75	33.1	+4.25%
Proportion renewable dispatch (%)	73.68%	76.71%	+4.11%
Curtailed renewables (TWh)	4.44	4.4	-1.1%
Proportion of renewables curtailed (%)	12.3%	11.7%	-4.87%
Fossil fuel dispatch (TWh)	10.8	9.53	-8.8%
Proportion fossil fuel dispatch (%)	25%	22.11%	-12%
Average marginal price (€/MWh)	125.5	122.25	-2.2%
Total cost of dispatch (€bn)	2.5	2.2	-10.9%
Carbon emissions ($MTCO_2$)	5	4.4	-12%

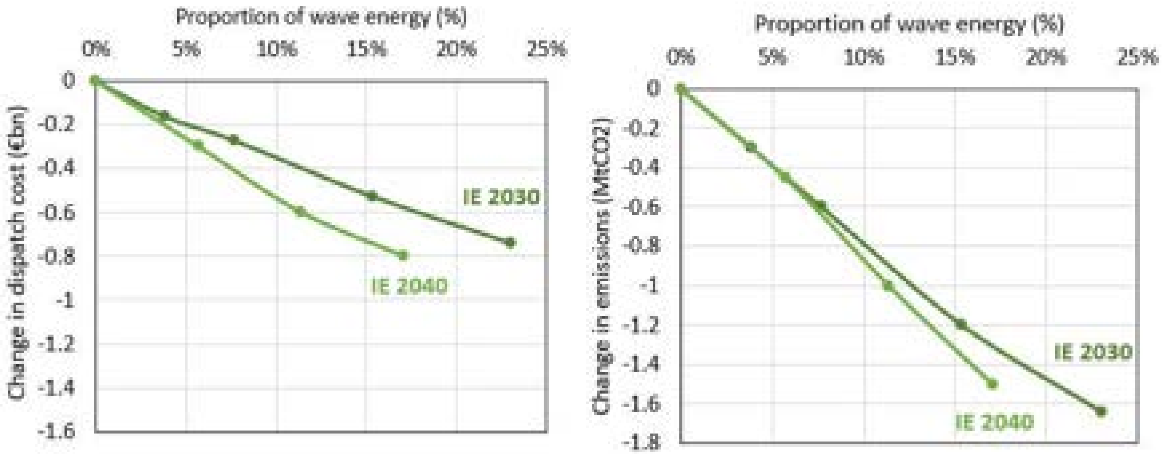


Figure 9. Cost (left) and carbon (right) reduction results from increasing proportions of wave energy within the Irish renewable mix. Each data point is from a separate model run, where the installed capacity of wave or tidal is increased in 1GW increments up to 3GW.

Table 4 shows the price capture of variable renewables in the baseline case and 1GW wave sensitivity. Wave generation can capture wholesale prices twice that of wind, as ocean energy generation profiles can be available at times of low wind resource. There is a very small amount of ocean energy (8MW) installed in the baseline case, and this small amount of wave captures higher wholesale prices than the scenario with 1GW. It can also be seen that the wave price capture is slightly lower than the solar price capture. This could be due to the very low proportion of solar power in the generation mix in Ireland, which will be temporally and seasonally offset from the other variable renewable energy sources of wind and wave.

Table 4 - Price capture results – 2030 IE scenario

Metric	Baseline case	Wave sensitivity (1GW)
Solar price capture (€/MWh)	177.5	159
Offshore wind price capture (€/MWh)	81	77.7
Onshore wind price capture (€/MWh)	95	76.6
Wave price capture (€/MWh)	176	158.6

3.3 PORTUGAL

The current Portuguese electricity system has an approximately even spread of fossil fuels (33% of installed capacity), hydroelectric (35% of installed capacity) and other renewables (32% of installed capacity). Portugal also has a carbon neutrality target by 2050, supported by a government roadmap [25].

Figure 10. Schematic of Portuguese grid [27]

Future electricity projections for Portugal are available in the Energy Scenarios in support of the Portuguese Strategy for Hydrogen (EN-H2) [6]. The strategy aims to move towards long term decarbonisation goals whilst integrating hydrogen as a sustainable energy vector.

It can be seen from Figure 11 that the installed capacity of wind and hydroelectric generation increases slightly between 2020 and 2040 in the Portuguese scenario. Solar PV generation is projected to increase considerably from 2020 onwards, with fossil fuels decreasing considerably between 2020 and 2030 especially.

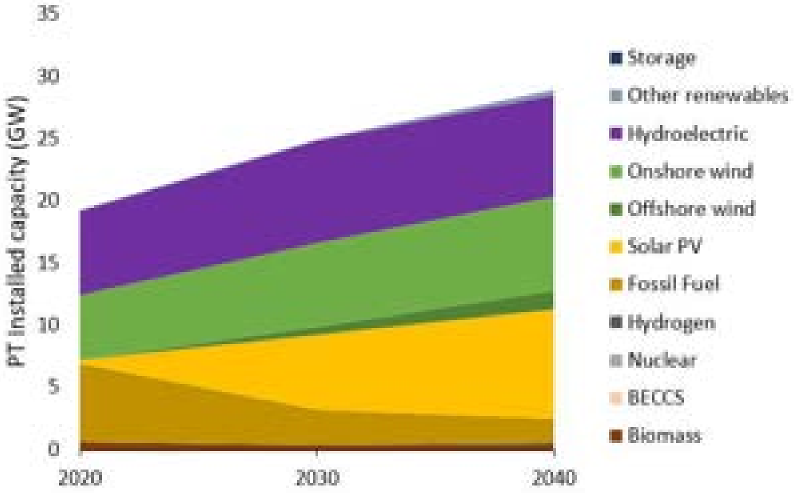


Figure 11. Installed capacity trajectory for Portugal, from Portuguese National Strategy for Hydrogen [6]

The modelling results for Portugal also show increased performance for the wave energy sensitivities over the nine metrics explored, shown in Table 5. Including 1GW of wave allows for more renewable energy to be dispatched, and thus less energy to be curtailed and less fossil fuels required to be dispatched. Including wave energy also decreases the total cost of dispatch, the average marginal price of dispatch and the resultant carbon emissions from generation dispatch. These metrics quantify the potential annual cost savings to the consumer from 1GW of wave energy as €230M.

Figure 12 shows the reduction in annual dispatch costs and carbon emissions when the proportion of wave energy increases within the Portuguese renewable energy mix, up to 1.5GW. This trend of cost and carbon reduction from including ocean energy continues with increasing penetration within the renewable mix. In this case, the cost reduction is higher for the 2040 scenario, by up to €600M from 1.5GW of wave energy, and the carbon reduction is higher in the 2030 scenario (as this scenario has the higher carbon intensity overall), by up to 660ktCO2 from 1.5GW wave energy in Portugal.

Table 5. System benefits from including 1GW of wave within the Portuguese 2030 energy mix, over nine metrics.

Metric	Baseline case	Wave sensitivity (1GW)	% difference
Renewable dispatch (TWh)	62.5	63.24	+1.2%
Proportion renewable dispatch (%)	91.5%	92.44%	+1.03%
Curtailed renewables (TWh)	0.02	0.016	-20%
Proportion of renewables curtailed (%)	0.03%	0.025%	-16.7%
Fossil fuel dispatch (TWh)	4.2	3.5	-16.7%
Proportion fossil fuel dispatch (%)	6.09%	5.11%	-16.1%
Average marginal price (€/MWh)	194.64	192	-1.4%
Total cost of dispatch (€bn)	5.43	5.2	-3.7%
Carbon emissions (MTCO$_2$)	2.13	1.78	-16.4%

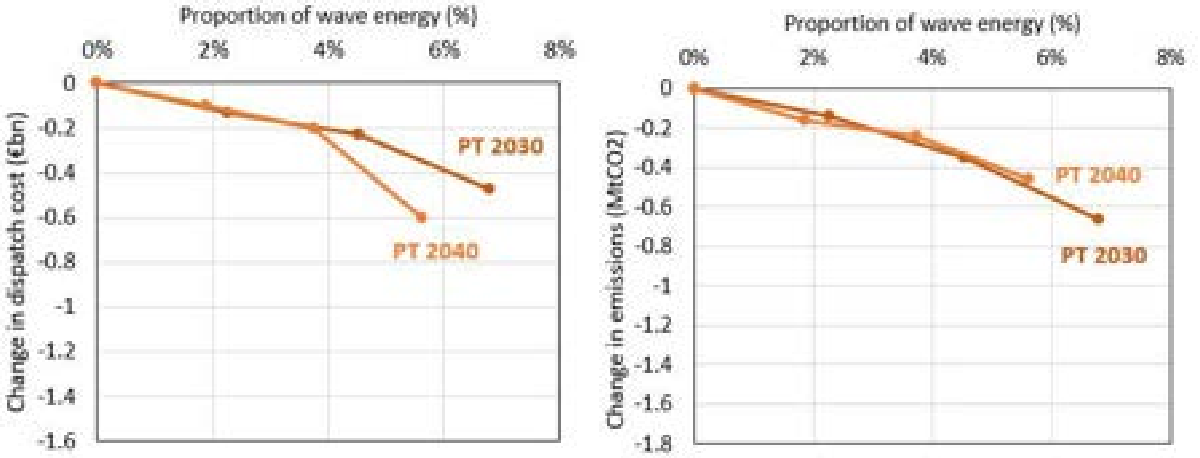


Figure 12. Cost (left) and carbon (right) reduction results from increasing proportions of wave energy within the Portuguese renewable mix. Each data point is from a separate model run, where the installed capacity of wave or tidal is increased in 500MW increments up to 1.5GW.

Table 6 shows the price capture of variable renewables in the baseline case and 1GW wave sensitivity. Wave generation can capture higher wholesale prices than wind and solar, as ocean energy generation profiles can be available at times of low wind or solar resource. There is a small amount of ocean energy (150MW) installed in the baseline case, and this small amount of wave captures higher wholesale prices than larger installed capacities of 1GW.

Table 6. Price capture results – 2030 PT scenario

Metric	Baseline case	Wave sensitivity (1GW)
Solar price capture (€/MWh)	176	173
Offshore wind price capture (€/MWh)	192.5	—
Onshore wind price capture (€/MWh)	191.5	191
Wave price capture (€/MWh)	196	193

4 DISCUSSION

4.1 REGIONAL RESULTS COMPARISON

The key result from this analysis is that including a higher proportion of wave or tidal within the energy mix has a significant impact on both annual dispatch costs and carbon emissions. Figure 13 illustrates this relationship for the 2030 scenarios for each of the three regions side-by-side, where the GB ocean energy deployment is 50% wave and 50% tidal, and the Irish and Portuguese ocean energy deployments are from wave energy only. It can be seen from these graphs that the relationship is close to linear between increasing proportions of ocean energy and decreasing costs and carbon emissions.

The cost and carbon reduction after 1GW of ocean energy is labelled for all regions on the Figure 13 results, with higher impacts for Ireland and Portugal than for GB. This is because 1GW of installed capacity makes up a much larger proportion of these electricity mixes, and thus can have more of an impact on dispatch. The cost and carbon results for 6GW of ocean energy is also labelled on the GB graphs, making up 4.7% of total installed renewables, compared with 1GW making up 7.7% of the Irish renewable electricity mix and 1GW making up 4.5% of the Portuguese renewable electricity mix. Interestingly, the cost and carbon reduction results between regions are more similar when comparing a similar proportion of renewable installed capacity, than when comparing 1 GW for each region.

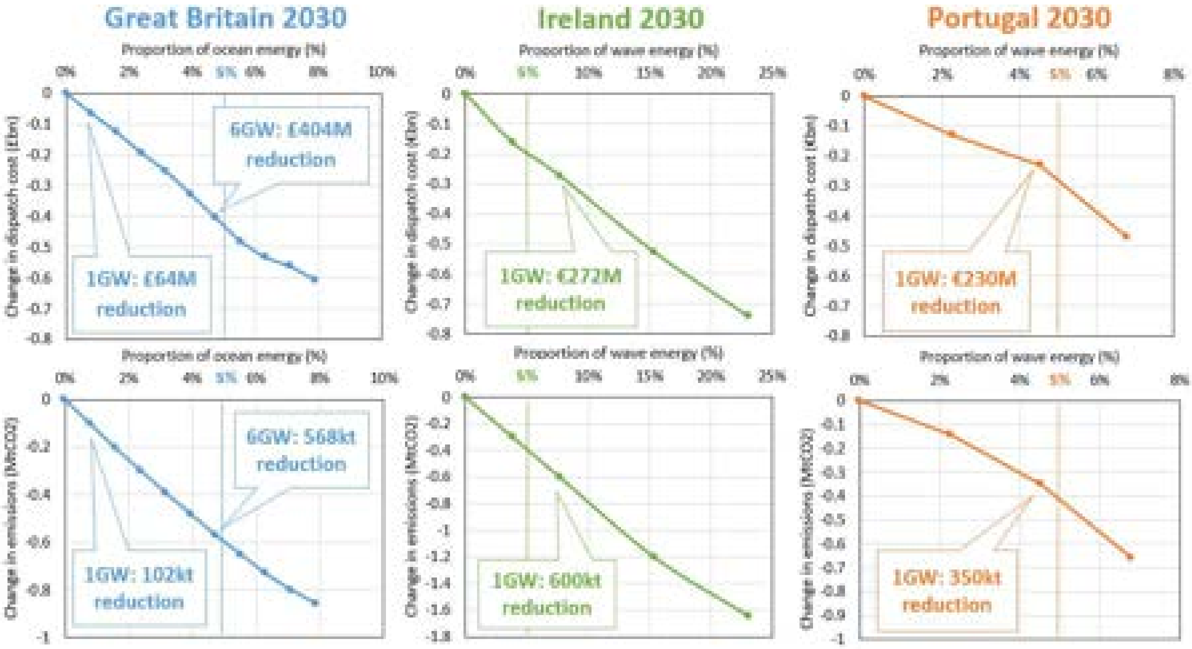


Figure 13. Impact on dispatch costs and carbon emissions for 2030 scenarios, all three regions.

4.2 LIMITATIONS AND UNCERTAINTIES

As with all types of modelling, there are limitations, simplifications and uncertainties that must be emphasized when presenting these results in order to fully understand them. It should be noted that although there are several sources of uncertainty discussed in the following paragraphs, they do not impact on the key results of this study – that we see consistent cost and carbon reduction from including ocean energy within high renewable future scenarios. This result has been found consistently across the majority of our scenarios and thus is a meaningful finding, even though the specific numbers reported are sensitive to many of the uncertainties discussed.

The modelling method chosen for this study is economic dispatch modelling. That is, the model objective function minimises the cost of dispatch with respect to several constraints (e.g. demand must be met for every hour, renewable generation can't exceed the resource availability). It is widely understood that economic dispatch modelling represents a simplified version of power system dispatch and electricity markets. The model optimises dispatch costs for 8760 time periods to represent one year, with perfect foresight of both demand and generation availability, and each type of generation bids into a perfectly competitive market based on their short run costs. As such, this form of modelling doesn't capture several real-world constraints on generation such as must-run or ramping constraints for large thermal units, or inertial constraints to ensure proper frequency response for the system.

In addition to this, the optimisation represents a pay-as-clear market, where every hour the market clears at the short-run cost of the most expensive generator, and all dispatched generators gain the same marginal cost. This is how wholesale electricity markets currently run in Europe, but it should be noted that many regions are consulting on new forms of electricity trading to support future low carbon, high renewable electricity mixes. As such, the market mechanism presented here may have changed significantly by the time we reach the 2040 and 2050 scenarios.

The future scenarios selected for our modelling represent a great deal of work performed by regional grid operators and governments. As such, they are credible potential deployment scenarios for each of our regions. However there is of course a lot of uncertainty associated with projecting future deployments up until 2050, and none of these future scenarios are presented as a forecast that will definitely occur – merely projections that can be used as a tool to focus policy and research decisions as Europe moves towards decarbonisation. The method we have used, adjusting the penetration of wave or tidal energy while keeping the amount of available renewable energy constant, is a further step of uncertainty onto these scenarios. It also moves these scenarios further away from the optimal modelled energy mix by the regional organisations that created them. As such, this work is intended as a 'what-if' analysis to illustrate the impact of higher proportions of ocean energy within the mix, using multiple points of data to discuss the general trends over various scenarios and sensitivities.

A range of uncertainties are also implicit within the modelling inputs and assumptions. These uncertainties have been explored within a number sensitivity analyses conducted on the GB 2030 scenario. Figure 14 illustrates the range of cost and carbon reduction outputs produced by adjusting the modelling inputs within reasonable limits. Some key outputs conclusions from the sensitivity analysis can be summarised as:

- Rather than basing the analysis on a single year (2019) of demand and renewable availability profile data, a sensitivity analysis has conducted using five separate years of input data (2015–2019 inclusive). It was found that the GB wave and tidal results are very sensitive to this input, and particularly to years with especially high or low wind resource.
- The potential for transmission constraints to impact on the dispatch of wave and tidal energy was considered, and model runs were conducted for the GB 2030 scenario including transmission constraints

based on National Grid's Electricity Ten Year Statement [26]. Sensitivity analysis showed tidal results are particularly sensitive to transmission constraints, as the majority of the tidal resource is located in the very north of Scotland. The tidal stream results in fact showed a clear inflection point when transmission constraints were included within the modelling, with costs and carbon emissions increasing once constraint limits had been reached. When adjusting the proportion of wave or tidal within the electricity mix beyond the base scenarios we can thus clearly see the impact of geographical position of different forms of renewable energy.

- Due to concerns with rising gas prices in 2022, a sensitivity analysis has been undertaken to investigate the impact of different gas price assumptions on the results, ranging between potential future gas prices both lower and higher than the base modelling inputs. The wave and tidal results have been found to be very sensitive to these inputs, with higher gas prices resulting in decreased dispatch of fossil fuels, but increased costs when fossil fuel dispatch is required.
- Finally, it is likely that the demand profile shape will change considerably as the heat and transport sectors are decarbonised, and more flexibility measures are introduced. A sensitivity was included to consider altering the demand profile shape to represent additional flexibility through smoothing, and the increased seasonal demands by increasing consumption in the winter months. It was found that the tidal stream results were particularly sensitive to these inputs.

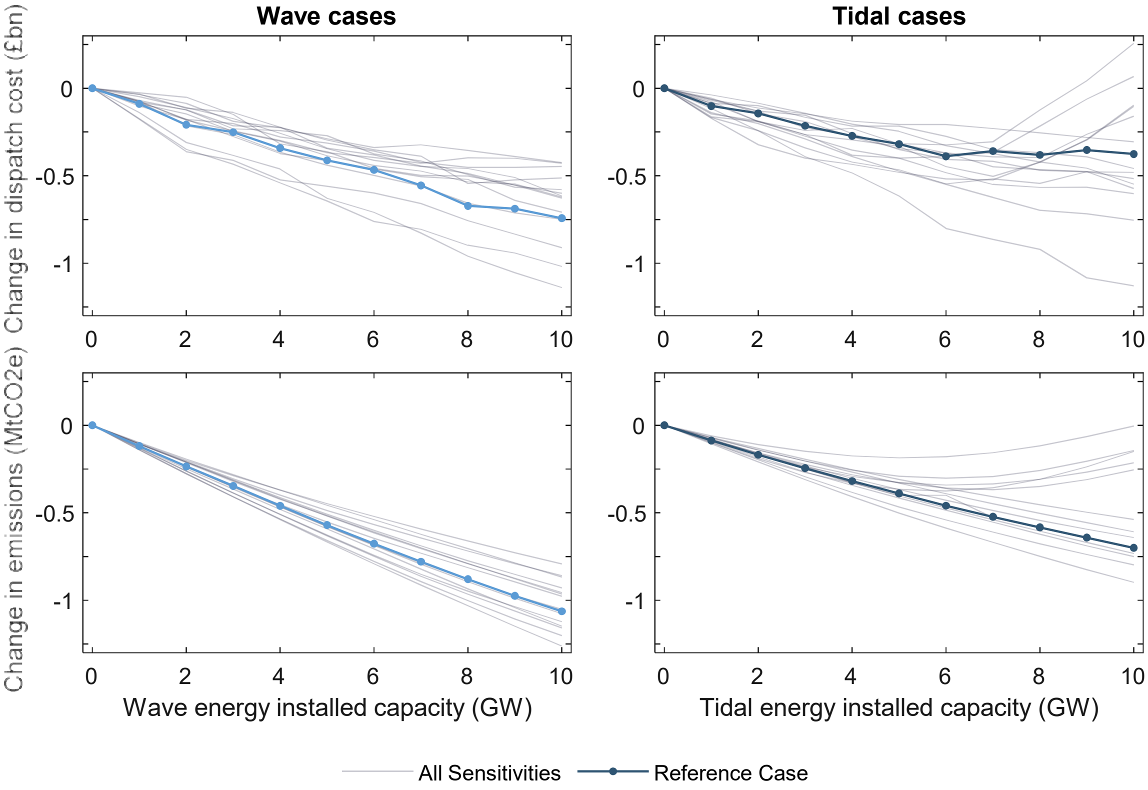


Figure 14. Summary of sensitivity analysis results, highlighting range of outputs resulting from 2030 GB modelling.

5 CONCLUSIONS

This technical note has detailed the country-scale economic dispatch modelling work undertaken for Great Britain, Ireland, and Portugal through the EVOLVE project. The purpose of the country-scale modelling in EVOLVE is to investigate the potential system benefit associated with including the deployment of ocean energy (wave and tidal stream) within future energy scenarios. The results indicate quantifiable benefits in terms of costs and carbon reduction when including ocean energy within the generation mix, compared to generation mixes with no ocean energy included. For example, the cost reduction results in this technical note range from £90M (1GW of wave in GB in 2030) to £1.46bn (10GW of wave in GB in 2040) and the carbon reduction results in this report range from 10 ktCO2 (1GW of tidal stream in GB in 2040) to 1.06 MtCO2 (10GW of wave in GB in 2030). Ocean energy is also able to capture up to 2.2× the wholesale price of wind (1GW of wave in GB in 2050).

These system benefits are due to the offsetting of ocean energy availability with other renewables such as wind and solar. It was found that a more diverse mix of renewables, including ocean energy, results in a more consistent renewable production profile which is better able to meet hourly electricity demand. System benefits from including ocean energy within the electricity mix have been observed for all 10 scenarios across the three regions, and 14 sensitivity analyses for the Great Britain 2030 LTW scenario.

This analysis is particularly meaningful as there are very few studies that quantify the system benefits associated with including ocean energy within country-scale power systems, and no studies that do so over quite so many regions. These results will be of interest to various stakeholders across the sector: technology and project developers, academic and industrial researchers, and grid operators and policy makers looking to develop future decarbonised systems whilst maintaining security of supply.

Finally, two further technical notes have been published by the EVOLVE project, showing the practical deployment potential for wave and tidal stream for the three EVOLVE regions of interest, and the potential system benefits of deploying ocean energy at an islanded microgrid level. The latter study has produced results consistent with the analysis presented here: increasing the proportion of wave and/or tidal stream within high-renewable future power systems results in a higher availability of renewable energy, and thus lower costs.

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