Supergen Offshore Renewable Energy

What are the UK power system benefits from deployments of wave and tidal stream generation?

A Supergen Offshore Renewable Energy Hub Policy Paper prepared by the Policy and Innovation Group at the University of Edinburgh.

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THE UNIVERSITY of EDINBURGH
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This report has been written by Shona Pennock and Henry Jeffrey from the Policy and Innovation Group.

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Supergen Offshore Renewable Energy Hub

The Supergen ORE Hub is a £9 Million Engineering and Physical Sciences Research Council (EPSRC) funded programme which brings together academia, industry, policy makers and the general public to support and accelerate the development of offshore wind, wave and tidal technology for the benefit of society. The Hub is led by the University of Plymouth, and includes Co-Directors from the Universities of Aberdeen, Edinburgh, Exeter, Hull, Manchester, Oxford, Southampton, Strathclyde, and Warwick. The Supergen ORE Hub is one of three Supergen Hubs and two Supergen Network+ created by the EPSRC to deliver strategic and coordinated research on Sustainable Power Generation and supply.
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WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

CONTENTS

1 EXECUTIVE SUMMARY

This study quantifies the potential power system benefits that the UK stands to gain through the deployment of marine energy technologies (wave and tidal stream) in domestic waters.

These system benefits are primarily due to the temporal and spatial offsetting of wave and tidal resource with other, more established variable renewables, such as wind and solar. Wave and tidal generation can be available at times of low wind or solar resource, helping to balance the overall renewable power profile. It has been found that a more diverse generation mix including marine energy is consistently more available and better able to meet demand than a renewable generation mix comprising of only wind and solar.

This study focuses on a 2050 net-zero compliant scenario for the power system of Great Britain. System benefits from marine energy are quantified over a range of metrics: increased renewable dispatch, decreased peaking generation and fossil fuel dispatch, decreased storage requirements and decreased dispatch costs.

This work is founded on deployment scenarios, where cost, performance, and systematic conditions are defined by the 2030 levelised cost of energy (LCOE) targets in the Strategic Energy Technology Plan for Ocean Energy. Deployment modelling obtained from the Energy Systems Catapult (ESC) forms the basis of the 2050 future energy scenarios used in this analysis. Scenarios both with and without marine energy are included, in order to compare the impact of including marine energy within the future generation mix.

The resultant deployment scenarios for 2050 have then been modelled using the EVOLVE Great Britain economic dispatch model. This model computes the least-cost supply-demand balance over a full year of electricity dispatch, at an hourly timescale, representing perfectly competitive wholesale market operation.

Results are also presented over a range of sensitivity analyses: five separate years of variable resource and demand profile input data are used to show the sensitivity of the results to particularly high or low wind years; and three gas price scenarios are used to show the sensitivity of the results to future gas price assumptions.

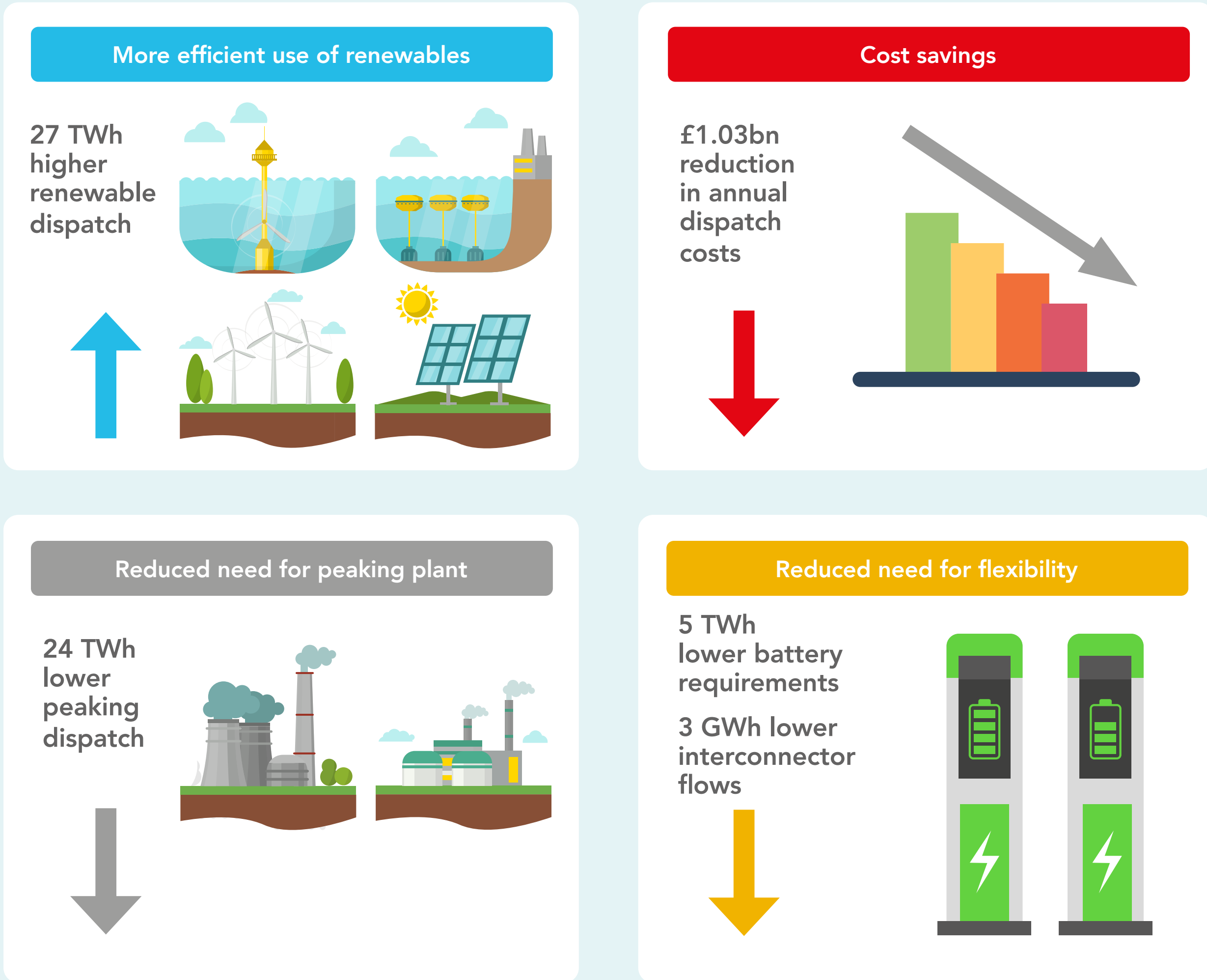
Results from this work can be summarised as:

- Energy planning modelling projects **6.4GW of wave** and **6.2GW of tidal stream** deployments in GB by 2050, if the SET Plan targets are reached by 2030.
- Previous work has shown that the resultant value to the UK economy from these deployments would be up to **£8.9bn Gross Value Added**.
- This study shows that the potential power system benefits of this 12.6GW deployment of marine energy would be up to **£1.03bn reduction in dispatch costs per annum**.
- This cost reduction comes from **a higher dispatch of renewable energy** – by up to 27 TWh (+6%), and thus **a lower requirement for expensive peaking generation** – by as much as 24 TWh (-16%) when wave and tidal generation are part of the electricity mix, compared with a scenario without marine energy generation.
- Additionally, the scenario which includes marine energy demonstrates a higher ability to meet domestic (GB) demand with domestic generation, as it requires **5 TWh less (-65%) battery use and 3 GWh less (-6%) energy imports over interconnectors**.

Several sensitivity analyses have also been performed, and it has been found that the general trend in results is consistent between every sensitivity scenario, that is: **a higher penetration of marine energy results in lower dispatch costs, higher renewable dispatch, lower peaking generation and flexibility requirements.**

It should be noted that the scope of this work is the GB grid (comprising Scotland, England and Wales). The whole of Ireland is a separate power system and market, and so Northern Ireland, although part of the UK, does not fall within the geographical scope for this study.

What are the 2050 GB power system benefits from 12.6GW of wave and tidal stream?



This analysis is particularly meaningful as there are very few studies that quantify the system benefits associated with including marine energy within country-scale power systems. 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.

It should be noted that these system benefits to the GB power system are only achievable if focused investment in marine energy technologies enables a reduction in LCOE in line with the SET Plan targets. This results from performance improvements and cost reduction both through innovative step-changes in research and development and through learning from continues successive deployments.

2 INTRODUCTION

Orbital Marine Power's O2 at EMEC in Orkney (Courtesy Orbital Marine Power).

Marine Energy technologies could play a key role in meeting long-term decarbonisation targets, both in the UK and globally. These technologies can provide a range of benefits including economic growth (particularly in coastal communities), reducing reliance on importing fossil fuels, emissions reduction, and meeting demand at times of low wind or solar generation.

This study quantifies the potential system benefit offered to the power system of Great Britain (GB) based on marine energy deployments. Marine energy, here defined as electricity generation from the wave and tidal currents, has a large but relatively untapped resource in Great Britain. This resource is often offset from other variable renewable resources such as wind and solar, and so could provide a complementary source of renewable generation. This study uses hourly economic dispatch modelling to investigate how this offsetting in generation profiles could impact on power system operation.

It should be noted that the scope of this work is the GB grid (comprising Scotland, England and Wales). The whole of Ireland is a separate power system and market, and so Northern Ireland, although part of the UK, does not fall within the geographical scope for this study.

Previous work has investigated the potential socioeconomic benefit that the UK stands to gain through marine energy deployments, in gross value added (GVA) terms. It was found that global deployments of wave and tidal stream technologies could produce a total of £11bn - £41bn in GVA to the UK economy by 2050, with £4.9bn - £8.9bn from domestic (UK) deployments (Figure 1) [1].

This socioeconomic benefit is dependent on the relative strength of the UK supply chain, and more specifically the spend retained within the UK from marine energy deployments.

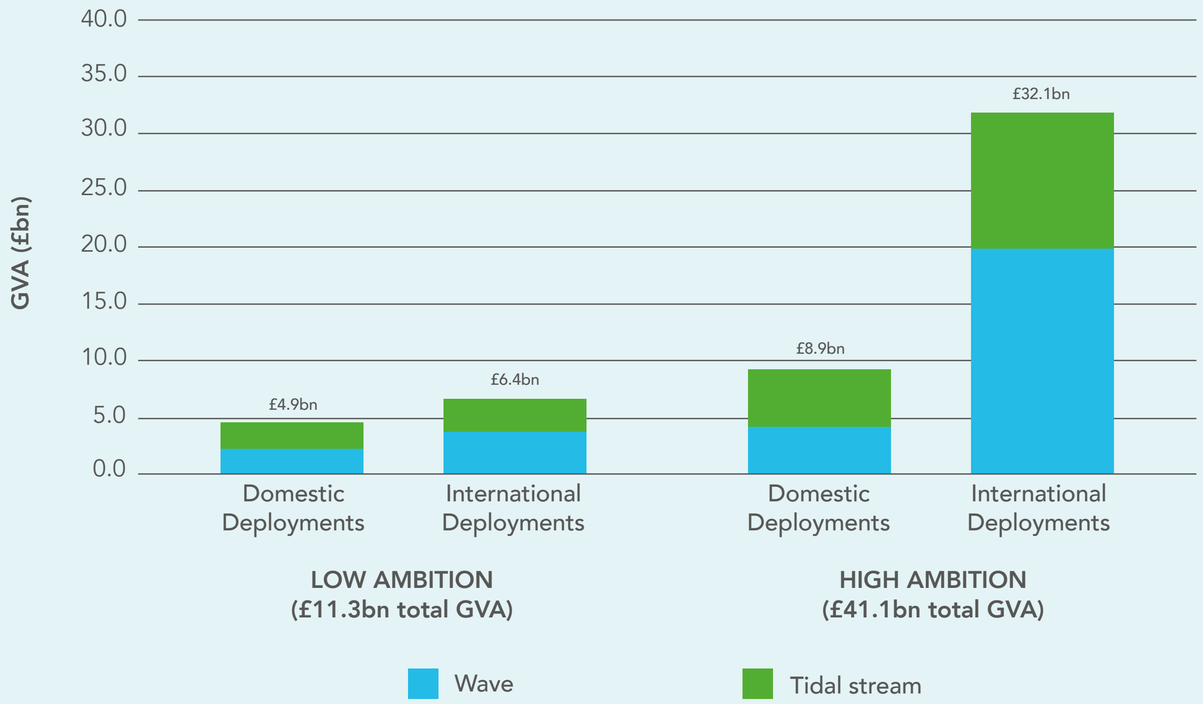


Figure 1 – GVA associated with domestic and international deployments when SET Plan targets are achieved by 2030 [1].

Marine Energy Technologies

This analysis focuses on the potential future deployment and resultant power system benefits of two marine energy technologies: wave and tidal stream. These technologies are of particular interest as they still require significant levels of innovation and cost reduction to become commercially mature. They also still have a wide scope for the UK to lead the way in terms of technology and supply chain development in the future.

Tidal stream has been deployed at array scale in the UK since 2016/17, at the Meygen and Bluemull Sound sites. Four tidal stream array projects have also gained market support from the Contract for Difference (CfD) Auction in 2022, totalling over 40 MW of deployment between 2025-2027. Orbital Marine Power won two contracts for a combined 7.2 MW in Eday, Orkney; SIMEC Atlantis won a contract for 28 MW in the Pentland Firth, Scotland; and Magallanes won a contract for 5.6 MW in Anglesey, Wales [2].

Wave technology is at a more nascent stage of development, with several single device demonstration projects ongoing. For example, five wave energy developers progressed to the second of the €20M Europe wave project in September 2022. Arrecife Energy Systems, AMOG Consulting, CETO Wave Energy, IDOM Consulting and Mocean Energy have been awarded continued funding to design and develop prototype devices intended for open-water trials by 2025 [3]. Further to this, Corpower Ocean are deploying their full-scale wave energy converter at Aguçadora, Portugal in late 2022, with array demonstration planned by 2025 [4].

Future cost and deployment targets have been established for these marine energy technologies through the Strategic Energy Technology Implementation Plan (SET Plan) for Ocean Energy [5] . The SET Plan aims to lead the clean energy transition in Europe, working towards the European Commission’s targets of 100MW of ocean energy by 2025 and at least 1GW by 2030 [6]. Coordinated by the SET Plan Working Groups, the SET Plans outline a structured approach that aids the progression of renewable energy technologies to commercialisation.

The cost targets for marine energy are:

- €100/MWh for tidal stream by 2030, and
- €150/MWh for wave energy by 2030.

Mocean Energy’s Blue X wave energy converter, at EMEC Scapa Flow test site (credit: Mocean Energy/Colin Keldie)

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

Quantifying the system benefits of marine energy

It has been found that wave and tidal availability is often offset from other renewables, such as wind and solar PV [7], [8]. Therefore, it could be of benefit to power system operation to include a more diverse mix of renewables which includes marine energy.

Previous studies have shown that marine energy generation profiles are more available and consistent than wind and solar generation [9], [10] and that combined generation profiles which include marine energy result in a lower variation of power output and lower instances of zero power output [11]. However, there are very few studies which quantify the power systems benefit in terms of cost.

Nova Innovation’s M100-D tidal turbine ‘Eunice’ (credit: Nova Innovation)

Resource offsetting between marine energy and other variable renewables are shown in terms of seasonal trends in Figure 2. These show demand and generation profiles based on a 2-week moving average, from historical electricity demand and renewable resource data from 2019. The values are normalised to the annual hourly peak.

Tidal Energy

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. It is also predictable for hundreds of years.

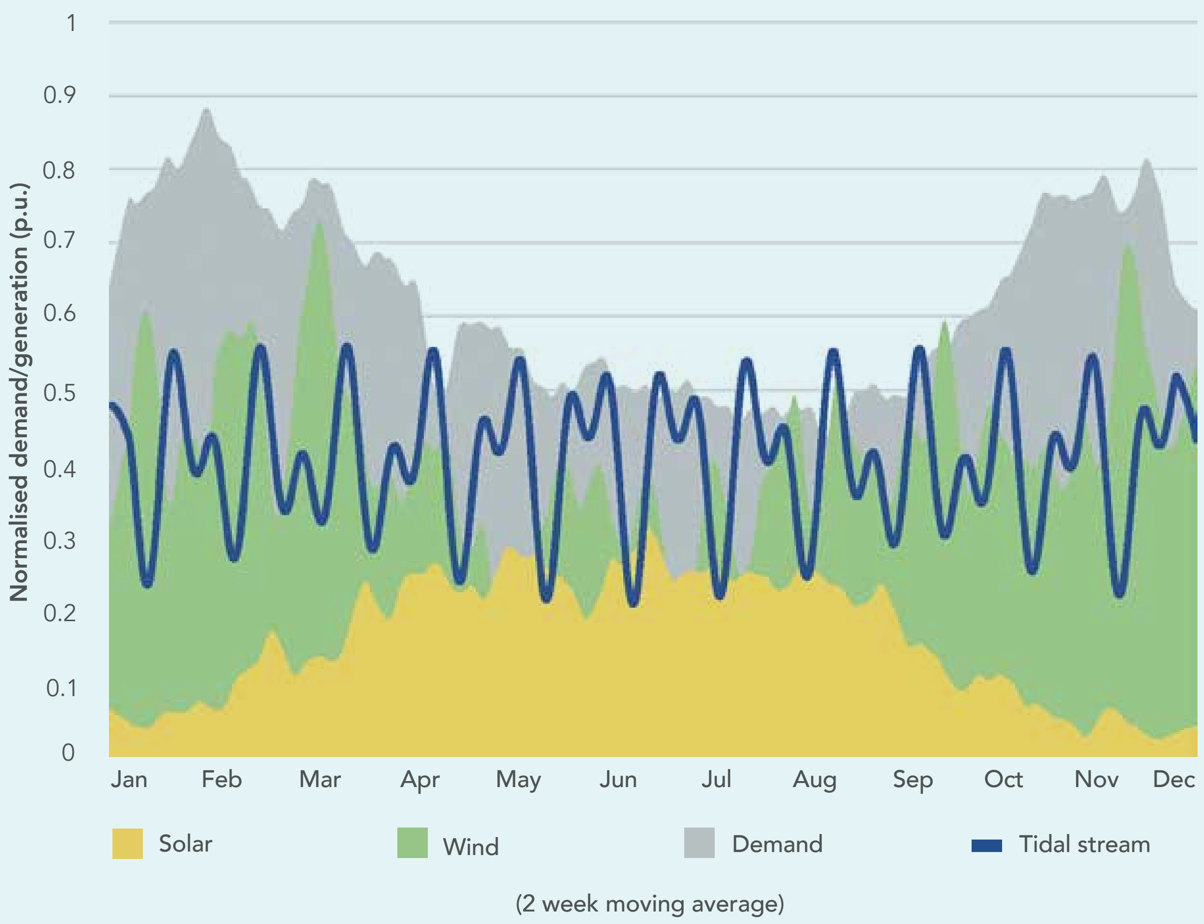


Figure 2a – Normalised demand and variable generation for GB, based on 2019 weather data, compared with tidal stream generation availability in 2019.

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

It can be seen from Figure 2 that electricity demand (in grey) is highly seasonal within GB, with higher demand in the winter months. Wind generation (in green) also has a seasonal profile, with higher peaks in winter. Solar generation (in yellow), conversely, is higher in the summer months.

Wave Energy

Wave energy is highly seasonal, with much higher resource in the winter months, correlating well with the demand profile. It is offset from the other variable renewables, and can be available at times of low wind or solar resource. Wave resource has been shown to be more predictable than wind resource [12].

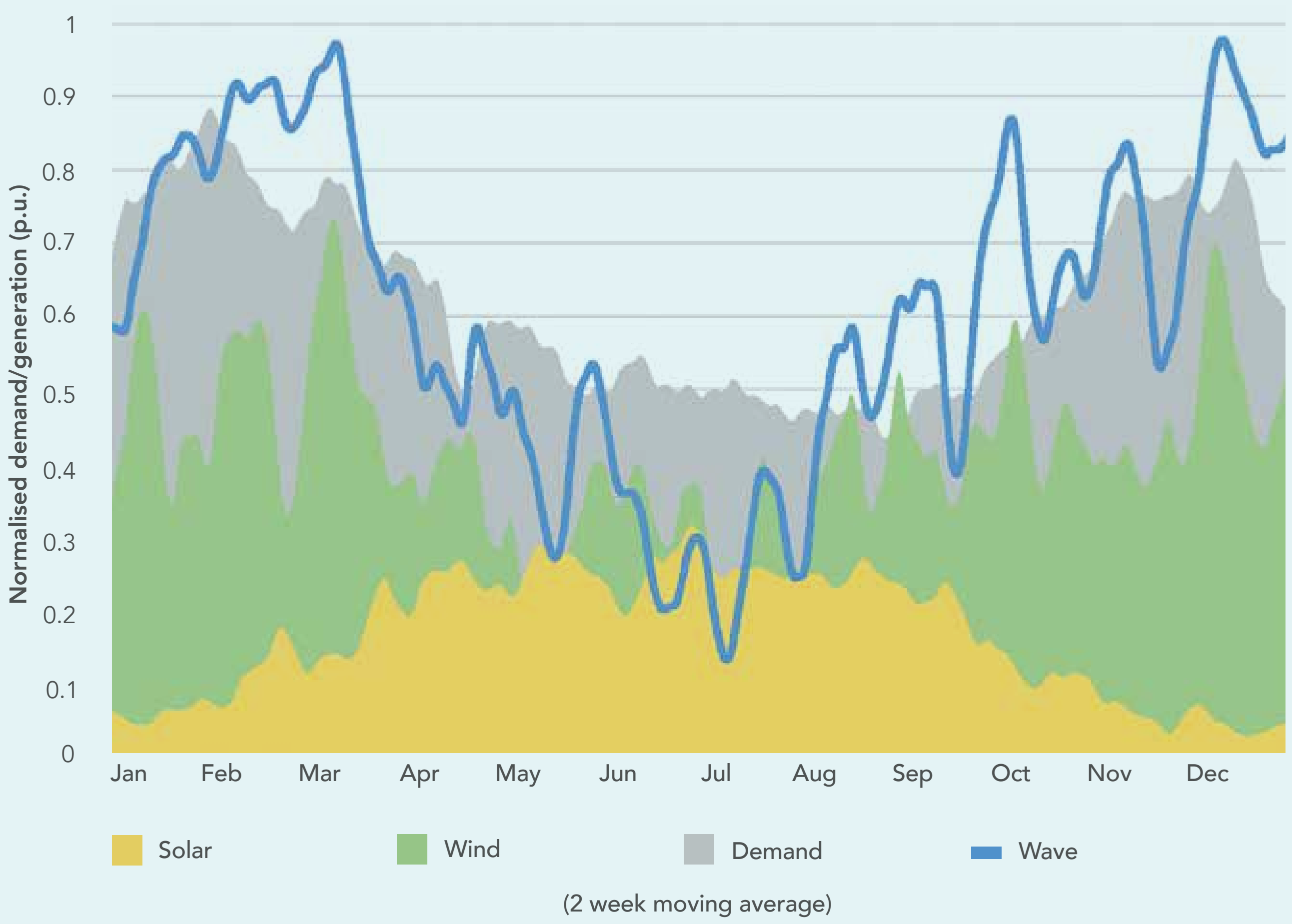
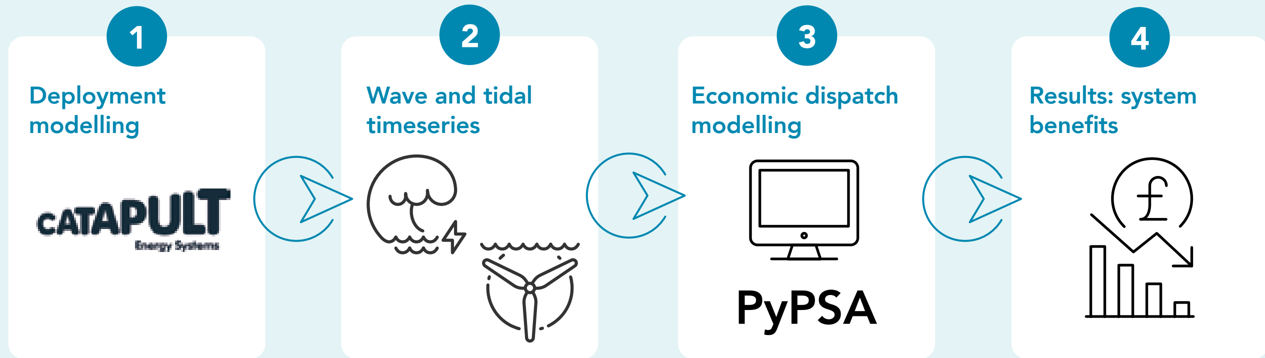


Figure 2b – Normalised demand and variable generation for GB, based on 2019 weather data, compared with wave generation availability in 2019.

3 METHODOLOGY AND INPUT ASSUMPTIONS

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION? Supergen Offshore Renewable Energy

In this study, the GB power system benefits associated with wave and tidal deployments are explored in terms of dispatch cost reductions, increased renewable energy dispatch and reduced peaking generation and storage requirements. The system benefits methodology is structured in four stages as illustrated below:



Step 1: Deployment scenarios based on the SET Plan targets were designed and modelled by the ESME modelling team at the Energy Systems Catapult (ESC). One scenario does not include any wave or tidal generation within the future electricity mix, and one allows the model to include wave and tidal generation as part of the optimisation, assuming that the SET Plan cost targets are met by 2030.

Step 2: Hourly timeseries of availability profiles have been generated for five forms of variable renewable generation: solar photovoltaic, onshore wind, offshore wind, wave, and tidal stream. These profiles all take historical renewable resource data from 2019 as a base year to ensure that the cross-correlations between variable renewable generation source, and with demand, are maintained.

Step 3: The deployment scenarios and variable renewable timeseries are input to the EVOLVE GB economic dispatch model. Python for Power System Analysis (PyPSA) software has been used to conduct this economic dispatch modelling, in which hourly electricity supply must meet hourly demand at least cost. This economic dispatch modelling represents a perfectly competitive wholesale market where generation bids are based on short term (fuel and carbon) costs.

Step 4: The power system operation is compared between the two deployment scenarios (one with and one without marine energy), to quantify the impact of including wave and tidal within the generation mix. The total cost and generation dispatch from both scenarios are compared, to produce results in terms of cost savings, renewable output, and storage usage.

Step 1: Wave and tidal deployment modelling

Deployment scenarios based on the SET Plan targets were designed and modelled by the ESME modelling team at the Energy Systems Catapult (ESC). One scenario does not include any wave or tidal generation within the future electricity mix, and one allows the model to include wave and tidal generation as part of the optimisation, assuming that the SET Plan cost targets are met by 2030.

The deployment modelling presented in this study is founded on the Energy System Catapult's Energy Systems Modelling Environment (ESME) tool. ESME is a whole systems modelling tool, used to create scenarios for the future GB energy system using a least cost optimisation algorithm, subject to system constraints such as annual energy demand and greenhouse gas emissions. The modelled FA96 scenario is aligned, in terms of 2050 greenhouse gas emissions, to the Committee on Climate Change's Further Ambition position defined in their Net Zero technical report [13] and used in the ESC's innovating to Net Zero analysis [14] [15]. As such, the energy mix is highly electrified and decarbonised.

A dedicated ESME run has been performed for this work, assuming that wave and tidal stream meet their SET Plan targets (€150/MWh and €100/MWh respectively) by 2030. Cost reductions and performance improvements beyond 2030 for wave and tidal stream are in line with those used in the European Commission Joint Research Council modelling [16]. The cost inputs, reductions, and performance improvements for all other technologies use standard ESME assumptions.

The resulting GB power system future deployments from the ESME model are shown in Figure 3. By 2050, 6.2 GW of tidal stream and 6.4 GW of wave have been deployed as part of the wider energy mix. As such, the ESME model produces a total of 12.6 GW installed capacity of marine energy technologies by 2050. The modelled 2050 mix has a high proportion of variable renewables, with around 200GW of wind, solar and marine. This high renewable electricity mix is also supported with low carbon dispatchable technologies such as gas with carbon capture, utilisation and storage (CCUS) and hydrogen.

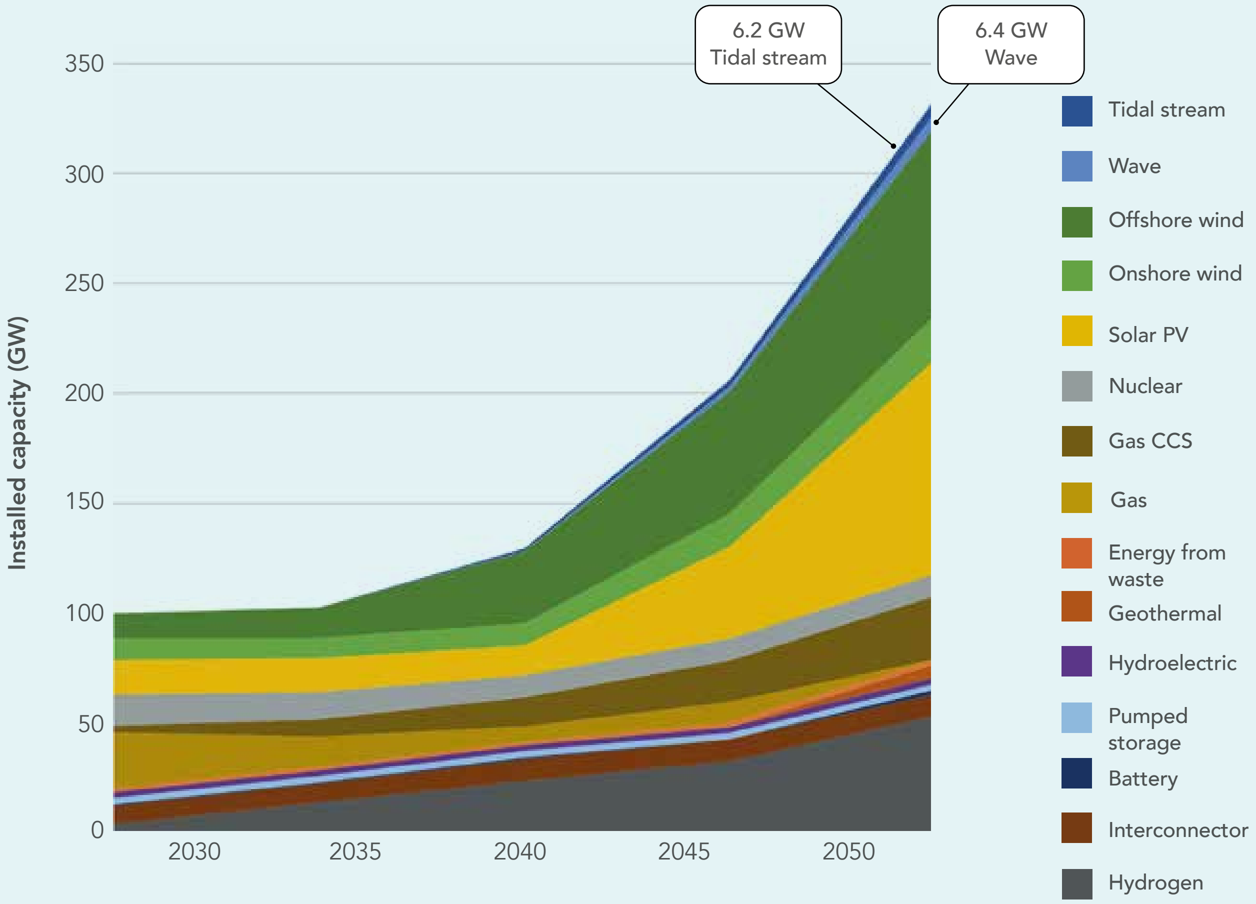


Figure 3 – Cumulative ESME model output GB deployments, 2030 – 2050.

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?
Supergen Offshore Renewable Energy

A base scenario without marine energy has also been run in ESME, in order to directly compare the economic dispatch results with the scenario where wave and tidal form part of the electricity mix.

The table below compares the 2050 deployment results for the two scenarios. It can be seen that the scenario which includes marine energy has less solar PV and less battery storage.

Table 1 – Generation installed capacity 2050 outputs from ESME modelling for scenarios both with and without marine energy.

Generation type	Without marine energy	With marine energy
Solar PV	112.9 GW	97.6 GW
Onshore wind	20.0 GW	20 GW
Offshore wind	85.4 GW	85.4 GW
Wave	0 GW	6.4 GW
Tidal stream	0 GW	6.2 GW
Nuclear	10 GW	10 GW
Hydrogen	40 GW	40 GW
Gas - unabated	0 GW	0 GW
Gas with CCUS	28.2 GW	28.8 GW
Hydroelectric	2.7 GW	2.7 GW
Energy from waste	2.4 GW	2.4 GW
Geothermal	9 GW	6.0 GW
Interconnectors	10 GW	10 GW
Battery storage	6.3 GW	1.9 GW
Pumped hydro	2.7 GW	2.7 GW
Total	**329.6 GW**	**320.1 GW**
Total renewables	**221.0 GW (67%)**	**218.3 GW (68%)**

Step 2: Wave and tidal timeseries

Hourly timeseries of availability profiles have been generated for five forms of variable renewable generation: solar photovoltaic, onshore wind, offshore wind, wave, and tidal stream. These profiles all take historical renewable resource data from 2019 as a base year to ensure that the cross-correlations between variable re-newable generation source, and with demand, are maintained.

Hourly timeseries of variable renewable generation availability is a key input to the economic dispatch modelling, so that the model can optimise hourly dispatch while accounting for variable renewable resource. Wind and solar resource data and power conversion models are readily available. In this case, the Renewables.ninja tool is used [17]. This software takes solar irradiance and wind speed data from NASA's MERRA reanalysis [18] and applies a Virtual Wind Farm model [19] and a Global Solar Energy Estimator model [20] respectively to generate hourly wind and solar generation time series.

However, wave and tidal stream generation timeseries are not as readily available using public tools and data, and so have been created especially for this work. 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 [21]. 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. Tidal stream timeseries 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 – as discussed in detail in [8].

Locations for wave and tidal stream sites around the British Isles are shown in the figure opposite.

South side view of the Morlais Tidal Energy Zone (credit: Marine Energy Wales)

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

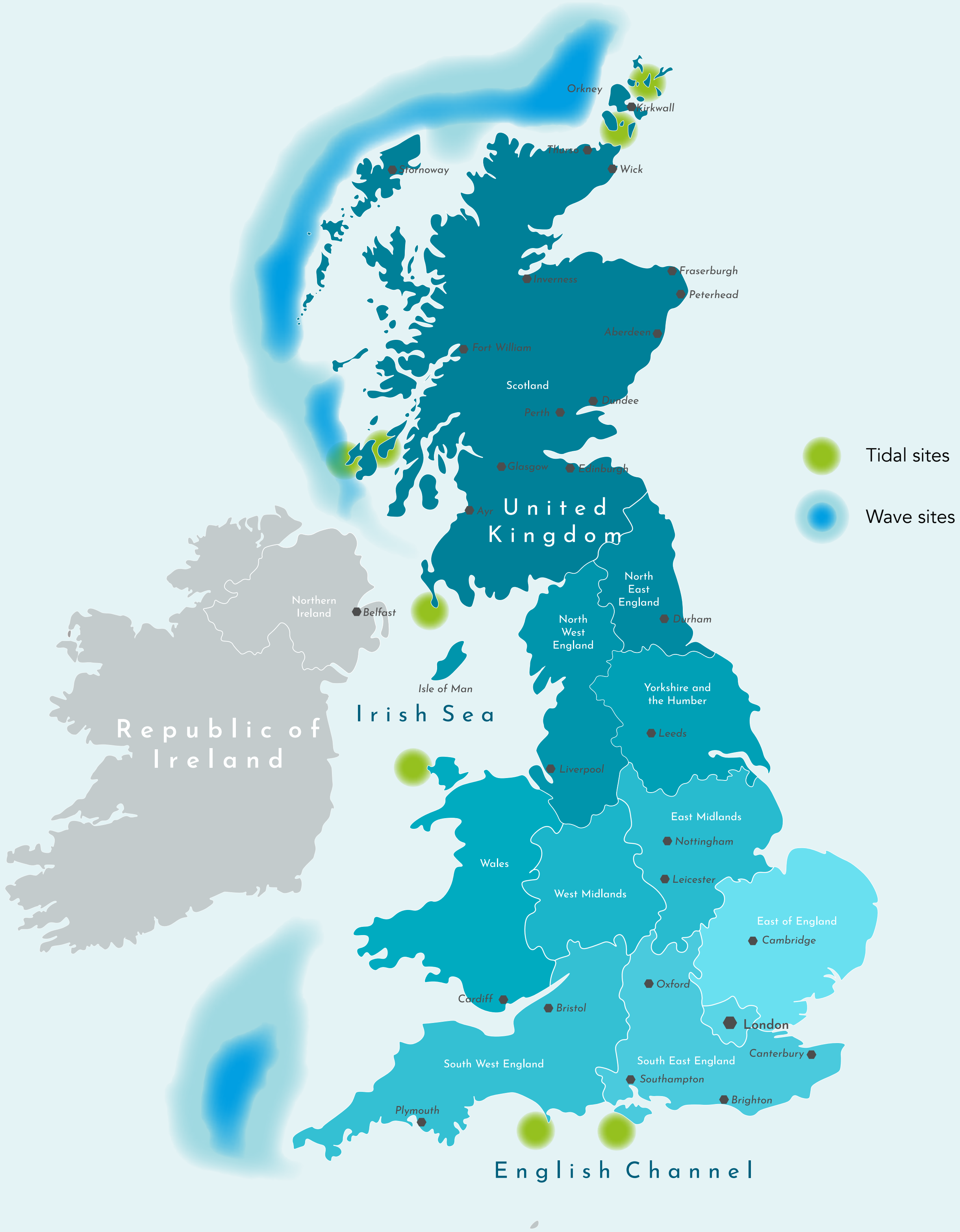


Figure 4 – Regions of high wave and tidal resource used to create input timeseries for this study.

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

Step 3: Economic dispatch modelling

A representative model of the GB power system has been created using Python for Power Systems Analysis (PyPSA) open-source power system operation software [22]. The key inputs, outputs and calculations are described and illustrated in Figure 5.

Inputs

The key inputs to the economic dispatch model are:

- Hourly demand profiles – taken from historical 2019 hourly GB demand [23], and scaled up to meet the total and peak ESME demand in 2050.
- Generation and storage installed capacity – taken directly from ESME deployment outputs.
- Renewable generation hourly availability timeseries – developed from 2019 wind, solar, wave and tidal resource data, as described in Step 2.
- Fuel and carbon costs – taken from Department of Business, Energy and Industrial Strategy projected future electricity generation costs [24].

Calculations

The linear optimal power flow equations were selected within the PyPSA software to minimise the costs associated with hourly dispatch for a full year of operation. Modelling constraints are included, relating to demand-supply matching, renewable availability profiles and storage capability. This economic dispatch optimisation represents a perfectly competitive wholesale market with perfect foresight of load and generation availability. Generation bids are based on short-term (fuel and carbon) costs, and the market clears at the price of the marginal generator in every hourly timestep. This hourly marginal price (representing the wholesale market price for electricity) is paid to every dispatching generator, and the model aims to minimise the total cost of dispatch over the 8760 hours of one year.

Outputs

The key outputs from the modelling are:

- Hourly marginal cost of electricity – used to calculate the energy-weighted average marginal cost of electricity, and the total dispatch cost incurred.
- Hourly dispatch of generation, storage, and interconnection – used to calculate the total dispatch from renewables, peaking generation, batteries, and interconnectors.

These outputs are compared between two scenarios:

1. **Without marine** – a baseline with no wave or tidal deployments, and
2. **With marine** – the 12.6GW wave and tidal deployments from the ESME modelling, where marine energy reaches sufficient cost reduction to be included within the energy planning model optimal results.

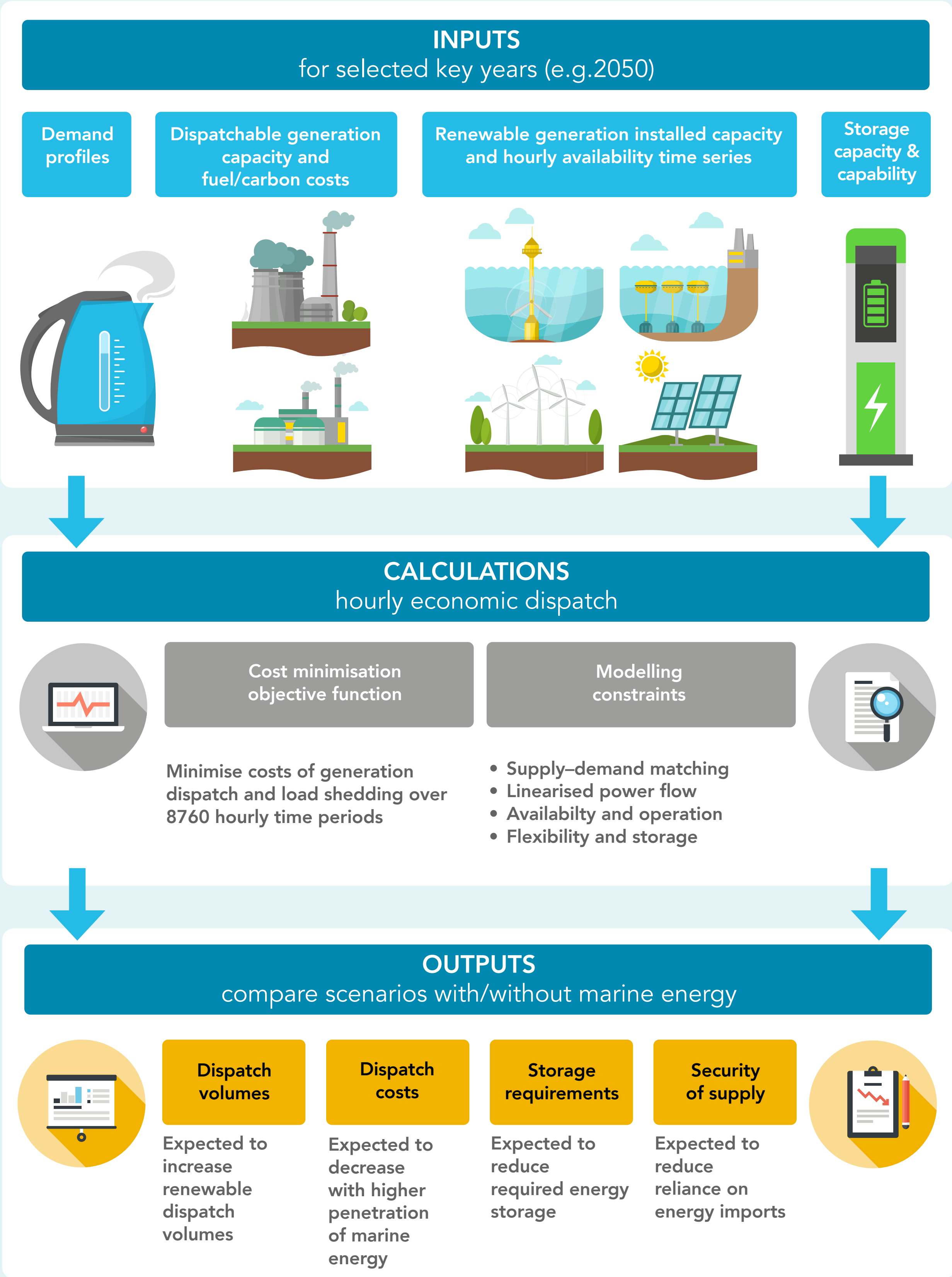


Figure 5 – Economic dispatch modelling illustration.

4 SYSTEM BENEFIT RESULTS

Simulated combined wind and wave farm (Courtesy CorPower Ocean)

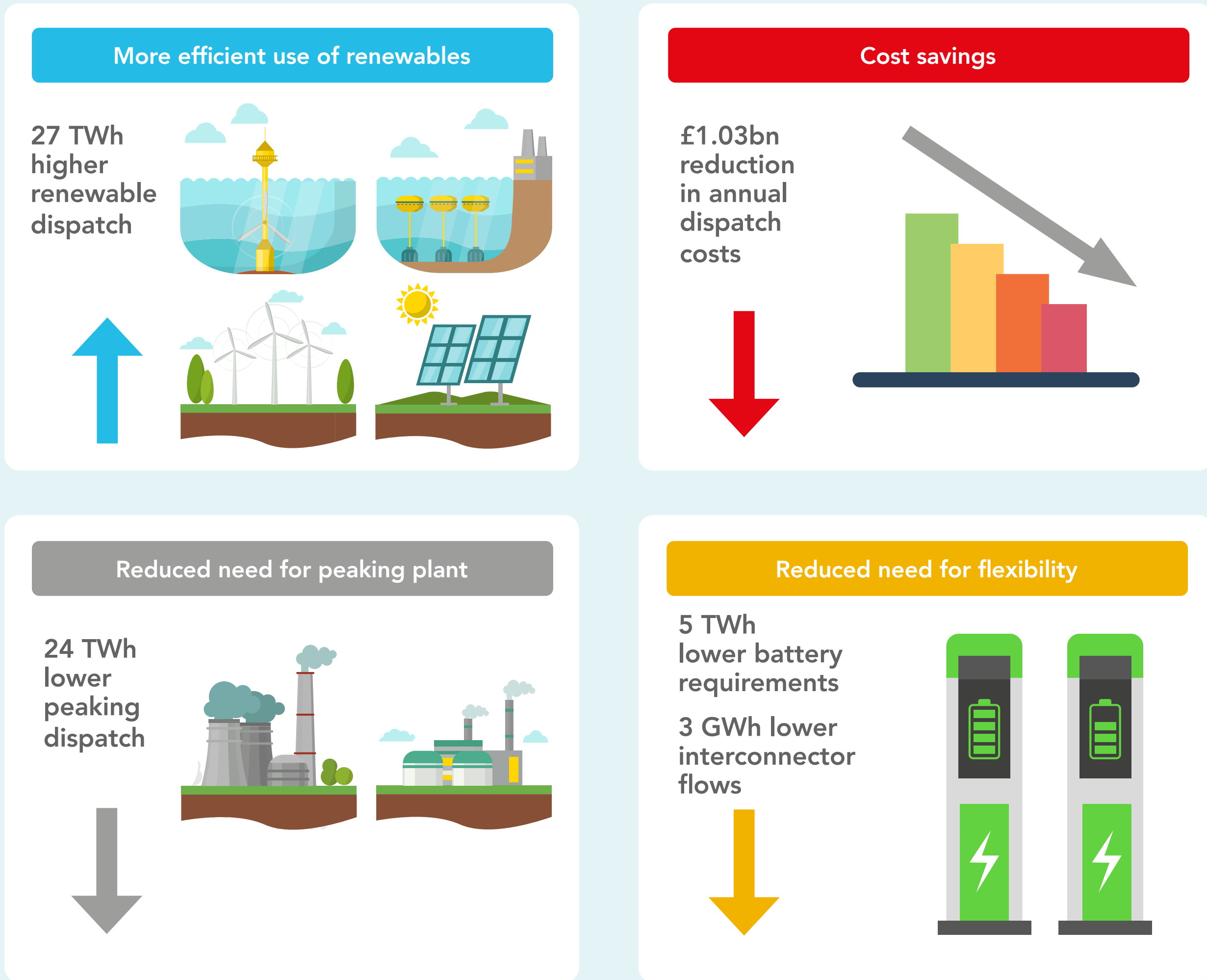
WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?

This study shows that the potential power system benefits of 12.6GW deployment of marine energy by 2050 would be up to £1.03bn reduction in dispatch costs per annum.

This cost reduction comes from a higher dispatch of renewable energy – by up to 27 TWh (+6%), and thus a lower requirement for expensive peaking generation – by as much as 24 TWh (-16%) when wave and tidal generation are part of the electricity mix, compared with a scenario without marine energy generation.

Additionally, the scenario which includes marine energy demonstrates a higher ability to meet domestic (GB) demand with domestic generation, as it requires 5 TWh less (-65%) battery use and 3 GWh less (-6%) energy imports over interconnectors.

What are the 2050 GB power system benefits from 12.6GW of wave and tidal stream?



Example week of generation dispatch

Scenario comparison is used to explore the difference in hourly dispatch between scenarios with and without marine energy deployments.

Figure 6 illustrates one week of dispatch for both scenarios -the first 168 hours in January. The wind resource (in green) is highest at the beginning and at the end of this week, with a particular dip in wind output on days 2, 3 and 6. On these days, higher volumes of peaking generation (hydrogen, Gas CCUS, Energy from Waste etc) are required, as well as higher utilisation of batteries and pumped hydro storage.

However, when comparing the scenarios with and without marine energy, it can be seen that there is more renewable energy available at times of low wind resource when wave and tidal are included within the energy mix. This results in lower requirements for peaking generation and battery storage for the scenario with marine energy deployments.

Without marine

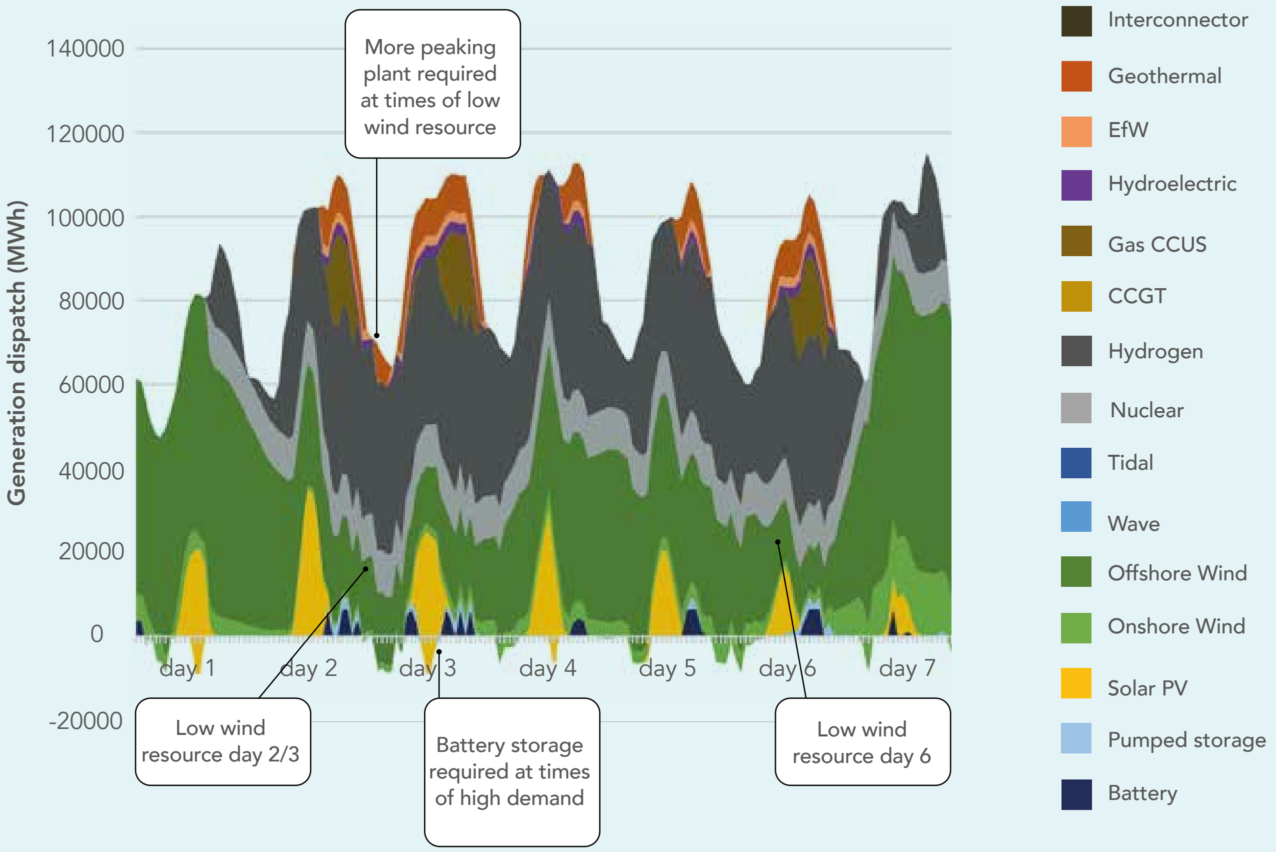


Figure 6a – weekly dispatch from EVOLVE GB economic dispatch model, showing first week in January from 2050 scenarios, without marine energy.

With marine

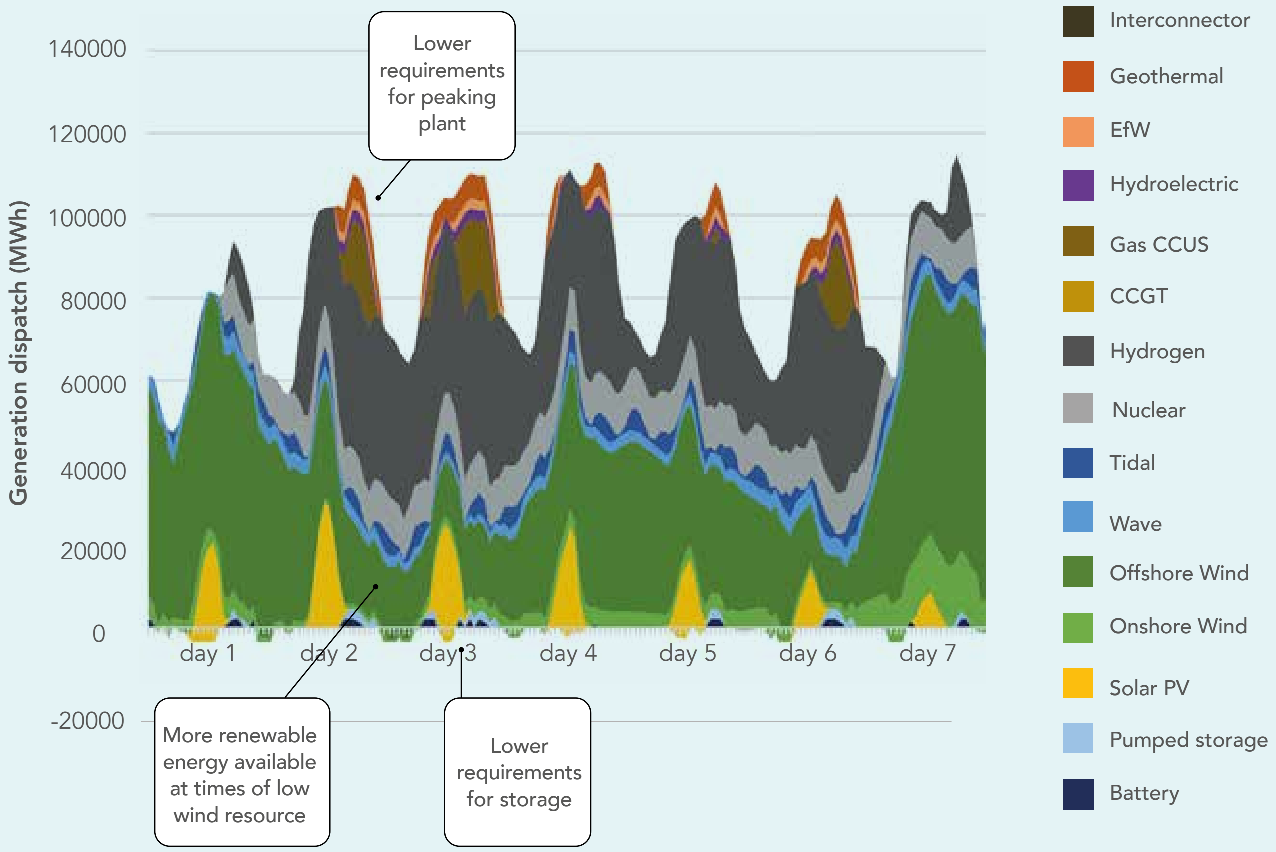


Figure 6b – weekly dispatch from EVOLVE GB economic dispatch model, showing first week in January from 2050 scenarios, with marine energy.

Results – full year of generation dispatch

We see these same trends continue over the full year of dispatch, with a total of 26.8 TWh higher renewable dispatch for the scenario which includes marine energy. This equates to 5.6% higher utilisation of renewables to meet the same total demand when wave and tidal are included within the energy mix, due to offsetting of these resources with existing wind and solar generation.

The higher dispatch from renewables also results in lower requirements for peaking generation (reduces by 15.6%), batteries (reduces by 65.3%) and imports from interconnectors (reduces by 5.5%), as shown in Table 2.

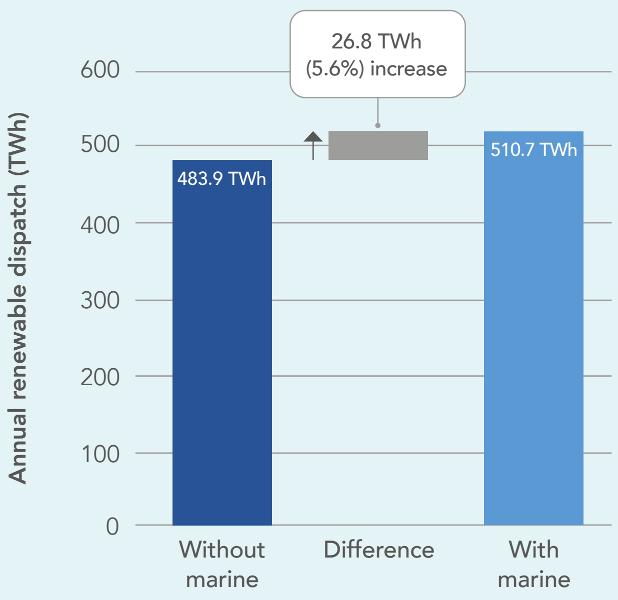


Figure 7 – Total annual renewable dispatch comparison between 2050 scenarios with and without ocean energy.

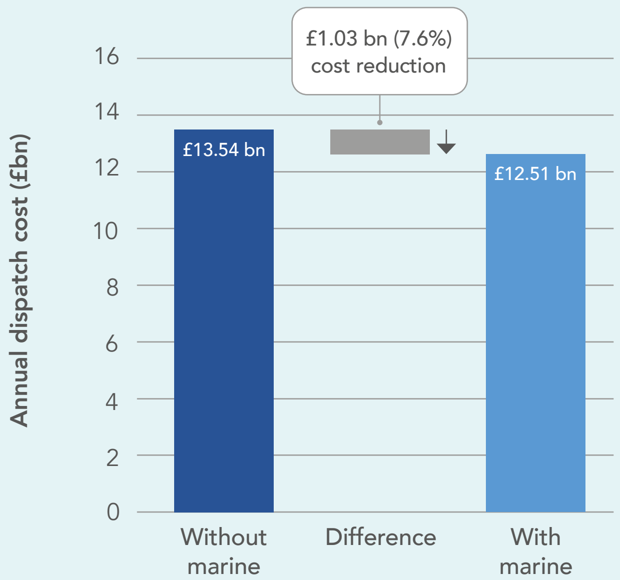


Figure 8 – Total annual dispatch cost comparison between 2050 scenarios with and without marine energy.

The increased utilisation of renewable energy results in an overall reduction in dispatch costs for the full year of power system operation – a £1.03bn (7.6%) reduction. It should be noted that the 12.6GW of marine represents only 4% of the total installed capacity.

This cost reduction is a result of the higher renewable dispatch, as renewables have no fuel or carbon costs and can thus bid into energy markets at very low short-run costs. Displacing expensive peaking generation with renewables therefore reduces the total annual cost of dispatch.

Table 2 – Comparison between 2030 scenarios with and without marine energy, over 7 metrics.

Metric	Without marine energy	With marine energy	Difference	Percentage change
Renewable dispatch	483.9 TWh	510.7 TWh	+26.8 TWh	+5.6%
Battery use	7.1 TWh	2.5 TWh	-4.7 TWh	-65.3%
Peaking generation	150.8 TWh	127.3 TWh	-23.5 TWh	-15.6%
Fossil fuel use	4.1 TWh	3.8 TWh	-0.3 TWh	-7.3%
Interconnection requirement	0.058 TWh	0.055 TWh	-0.003 TWh	-5.5%
Annual dispatch cost	£13.54bn	£12.51bn	-£1.03bn	-7.6%
Average marginal cost (£MWh)	£54.72/MWh	£51.79/MWh	-£2.93/MWh	-5.4%

This study shows that the potential power system benefits of 12.6GW deployment of marine energy by 2050 would be up to £1.03bn reduction in dispatch costs per annum.

This cost reduction comes from a higher dispatch of renewable energy – by up to 27 TWh (+6%), and thus a lower requirement for expensive peaking generation – by as much as 24 TWh (-16%) when wave and tidal generation are part of the electricity mix, compared with a scenario without marine energy generation.

Additionally, the scenario which includes marine energy demonstrates a higher ability to meet domestic (GB) demand with domestic generation, as it requires 5 TWh less (-65%) battery use and 3 GWh less (-6%) energy imports over interconnectors.

5 SENSITIVITY ANALYSES

Three sensitivity analyses have been undertaken on these results, to explore how sensitive the system benefits outputs are to the assumed rate of cost reduction for marine energy, the annual renewable available resource, and the gas price assumptions.

A more ambitious scenario where wave and tidal LCOE reduces at an even faster rate – to 80% of the SET Plan targets by 2030 – has been undertaken. In this case, the LCOE of **tidal stream reaches €80/MWh by 2030**, and **wave reaches €120/MWh by 2030**. This sensitivity shows additional benefits from higher installed capacities of marine energy in 2050: **up to £1.9bn reduction in dispatch costs per annum from 22.1 GW of wave and tidal energy**. This is due to a 10% increase in renewable dispatch, 27% decrease in peaking generation, 90% reduction in battery use and 20% reduction in import requirements, when compared with the scenario without marine energy.

Two sensitivities have also been undertaken on the base scenario (12.6GW of marine), investigating the range in results when adjusting the input year of weather data, and the gas price assumptions. **When accounting for these sensitivities the dispatch cost reduction from 12.6 GW of marine energy ranges from £0.75bn to £1.12bn.**

It is important to note that the general trend in results is consistent between every sensitivity scenario, that is: **a higher penetration of marine energy results in lower dispatch costs, higher renewable dispatch, lower peaking generation and flexibility requirements.**

Magallanes Renovables ATIR installation at EMEC, 2019 (Copyright Colin Keldie, Courtesy Ocean_2G)

How sensitive are the results to the marine energy cost reduction trajectory?

An additional scenario has been run in ESME to see what the resultant deployment of wave and tidal energy would be if the cost reduction trajectory were to exceed the SET Plan targets by 20% - i.e. reaching €80/MWh for tidal stream in 2030 and €120/MWh for wave.

The resultant deployment of marine energy was 22.1 GW for the reduced cost scenario, shown in comparison with the previous two scenarios in Figure 9. Increasing the installed capacity of wave and tidal generation again results in lower installed capacities of batteries, solar PV and geothermal.

The 22.1GW marine scenario was input to the GB economic dispatch model, and again compared with the economic dispatch results from the scenario without marine energy deployments. Again, it was found that the total amount of renewables able to be dispatched had increased, with 46.7 TWh higher renewable dispatch for the scenario with 22.1 GW of marine energy. This equates to 9.6% higher utilisation of renewables to meet the same demand when wave and tidal are included within the energy mix.

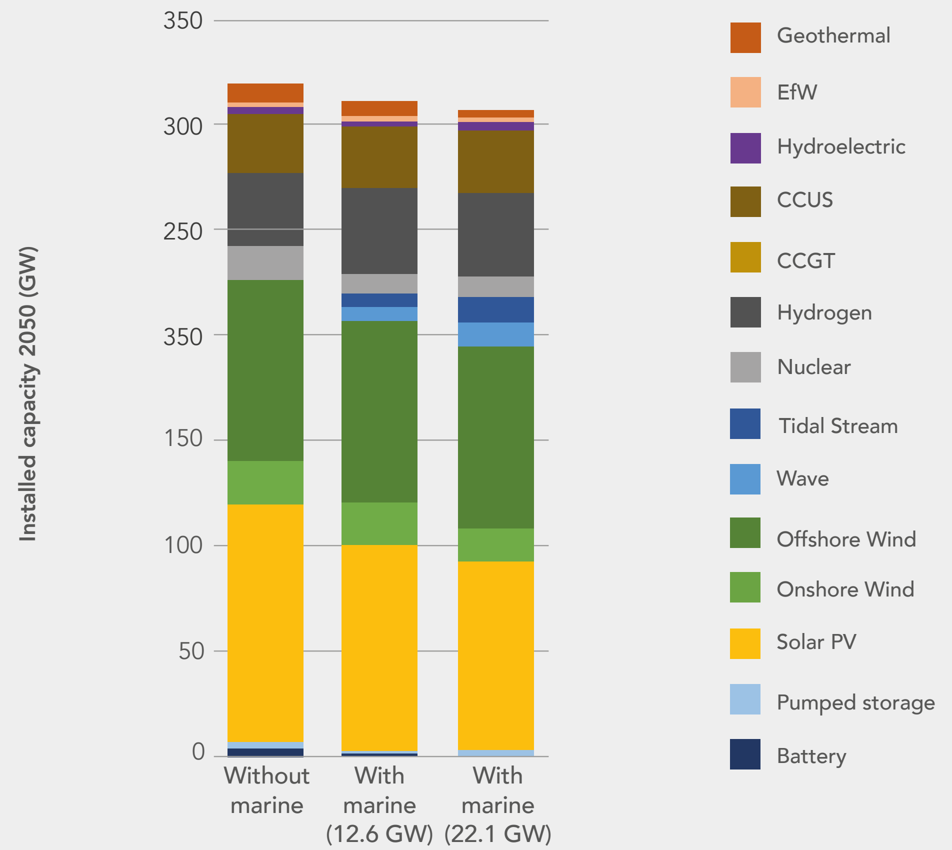


Figure 9 – Installed capacity comparison between scenarios with and without marine energy

Comparing the two marine scenarios, the increase in renewable dispatch from the 22.1 GW marine deployment scenario is almost twice that of the 12.6 GW marine deployment scenario, as shown in Figure 10.

For this scenario, the higher dispatch from renewables also results in lower requirements for peaking generation (reduces by 26.5%), batteries (reduces by 89.6%) and imports from interconnectors (reduces by 20.1%), as shown in Table 3.

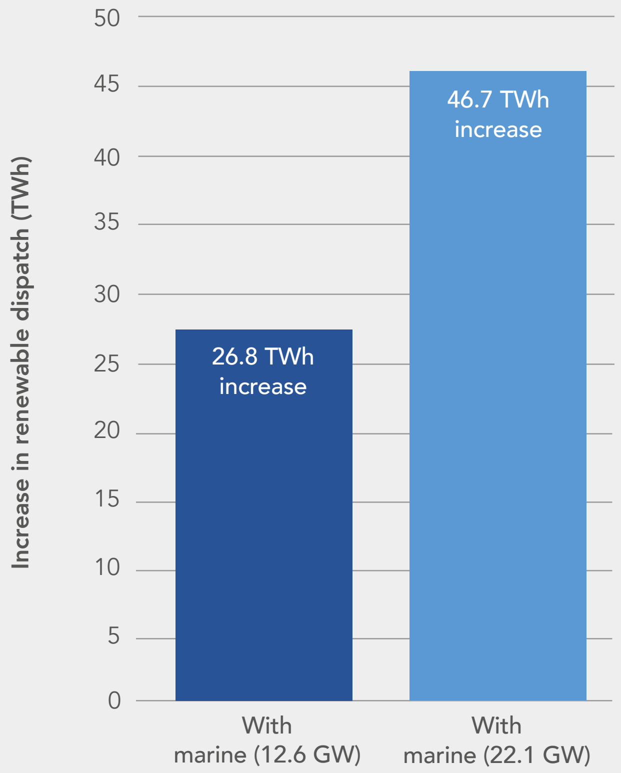
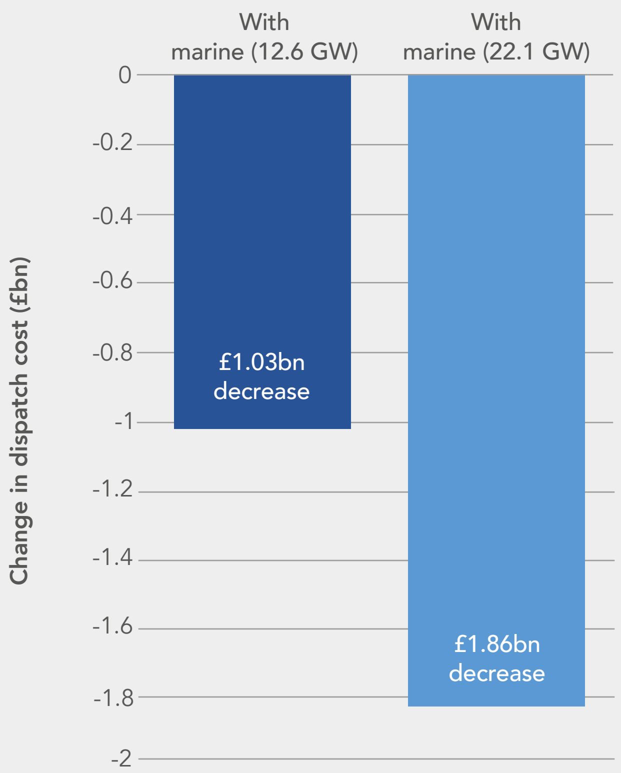


Figure 10 – Increase in renewable dispatch in scenarios with marine energy, both compared with scenario without marine energy



The increased utilisation of renewable generation and reduction in requirements for expensive peaking generation results in £1.86bn lower annual dispatch costs when compared with the scenario without marine energy. This represents a 14% reduction in the total dispatch costs compared with scenario without marine energy, but it should be noted that 22.1 GW of marine energy only makes up 7% of the total installed capacity.

Figure 11 – reduction in dispatch costs in scenarios with marine energy, compared with scenario without marine energy.

Table 3 - Comparison between 2030 scenarios without marine energy and with 22.1 GW of marine energy, over 7 metrics

Metric	Without marine energy	With marine energy (22.1 GW)	Difference	Percentage change
Renewable dispatch	483.9 TWh	530.6 TWh	+46.7 TWh	+9.6%
Battery use	7.1 TWh	0.7 TWh	-6.4 TWh	-89.6%
Peaking generation	150.8 TWh	110.8 TWh	-40.0 TWh	-26.5%
Fossil fuel use	4.1 TWh	3.4 TWh	-0.7 TWh	-16.9%
Interconnection requirement	0.058 TWh	0.046 TWh	-0.012 TWh	-20.1%
Annual dispatch cost	£13.54bn	£11.68bn	-£1.86bn	-13.7%
Average marginal cost (£MWh)	£54.72/MWh	£49.02/MWh	-£5.70/MWh	-10.4%

How sensitive are the results to annual renewable resource?

It is interesting to explore the sensitivity of the results to the annual renewable resource, to understand how the power system benefits are impacted by particularly low or high years of wind, solar, or wave resource.

To conduct this sensitivity, renewable resource data has been used for five consecutive years from 2015-2019. Each time the model is run, it is important to input the same year of hourly demand profile shape and hourly variable renewable availability profiles, to ensure that the cross correlations between different forms of renewable generation, and with demand, are maintained.

The resource availability of variable renewables in GB are compared over the five selected years in Figure 12. While solar and tidal availability are very consistent between the five years, wind and wave clearly show some years with higher (e.g. 2015) or lower (e.g. 2016) resource.

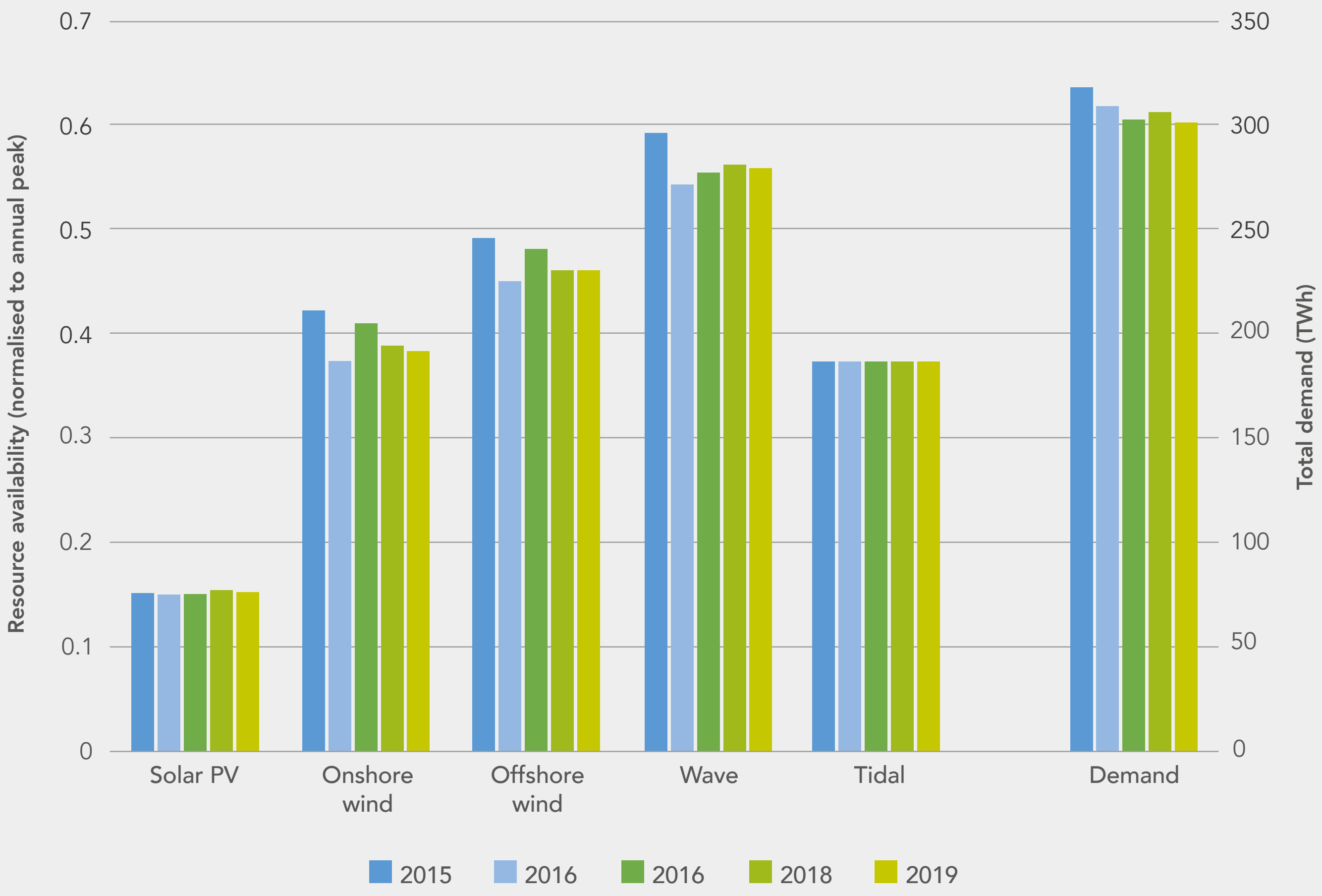


Figure 12 – Comparative resource availability of variable renewables over 5 years of data

It can be seen that although the results output for the multiple years differ, the general trend remains constant. The scenarios with marine energy consistently dispatch more renewable energy than the scenarios without marine energy, between 24.3 TWh to 26.9 TWh (4.8% - 5.5%) higher.

The requirement for peaking generation, batteries and interconnectors also reduces in the scenarios with marine energy, resulting in cost reduction figures between £750M and £1.03bn when compared with the scenarios without marine energy.

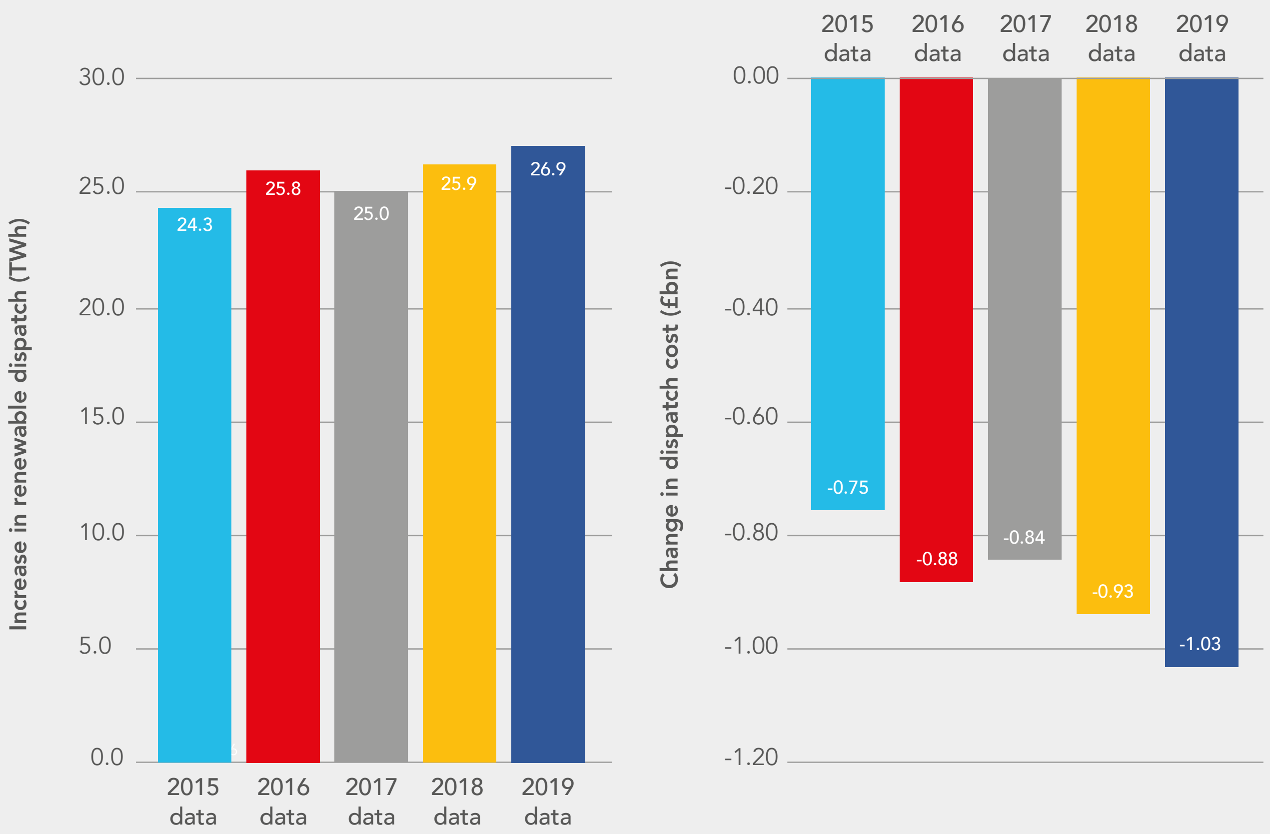


Figure 13 – Multi-year data sensitivity results showing increase in renewable dispatch from 12.6GW of marine energy (left) and decrease in dispatch costs (right).

How sensitive are the results to gas price assumptions?

Although there is not a very high installed capacity of gas plants in the 2050 scenarios (~30GW), recent years have shown future projections of gas prices are particularly sensitive to geopolitical influences. As such, the final sensitivity analysis explores the impact of gas price assumptions.

For this sensitivity two additional cases for gas price inputs have been undertaken in addition to the default value used in the previous analysis (here referred to as 'mid gas prices'). A 'low gas prices' case is used, in which the marginal price of gas with CCUS is 0.65x the rate in the 'mid gas prices' case, and a 'high gas prices' case is used, in which the marginal price of gas with CCUS is 1.45x the rate in the 'mid gas price' scenario. These price scenarios are based on the proportional difference between long term historical gas prices (low gas prices case), recent gas prices between 2020 – 2022 (mid gas prices case) and peaking gas price data over the winter of 2021-22 [25].

It can be seen that the gas prices input to the model do not impact greatly on the additional renewable dispatch results when including ocean energy to the mix. However, perhaps unsurprisingly, there is an impact on the dispatch cost savings from this increase in renewable dispatch. The scenarios with marine energy result in cost reduction figures ranging between £920M (low gas prices case) and £1.12bn (high gas prices case) when compared with the scenarios without marine energy. Thus the higher the gas prices are, the higher the cost reduction possible from marine energy.

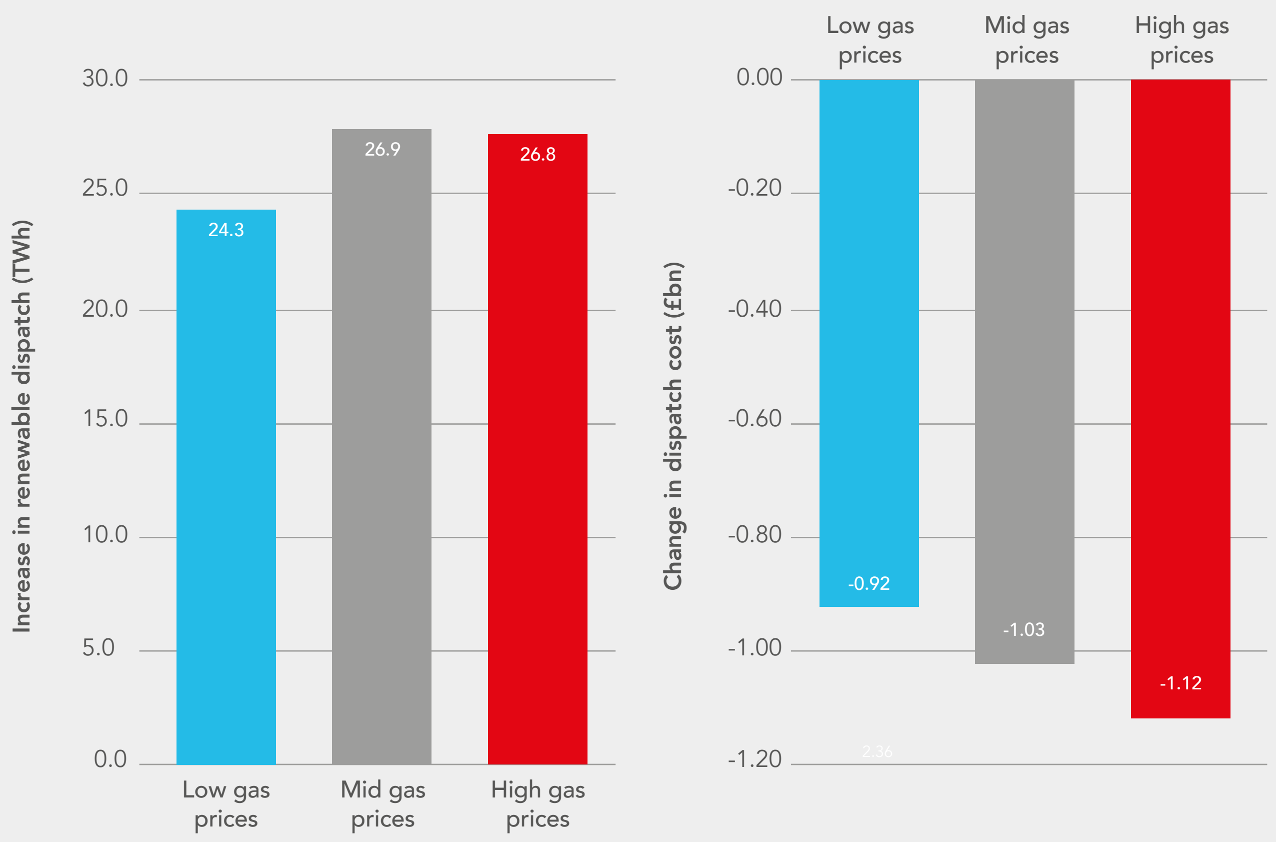


Figure 14 – Gas price sensitivity results showing increase in renewable dispatch from 12.6GW of marine energy (left) and decrease in dispatch costs (right).

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6 KEY MESSAGES

This work has explored the potential benefits to the GB power system associated with deploying marine energy technologies – namely wave and tidal stream. Deployment levels in 2050 have been based on the ESME GB energy systems model, assuming that these technologies meet their European SET Plan cost targets by 2030.

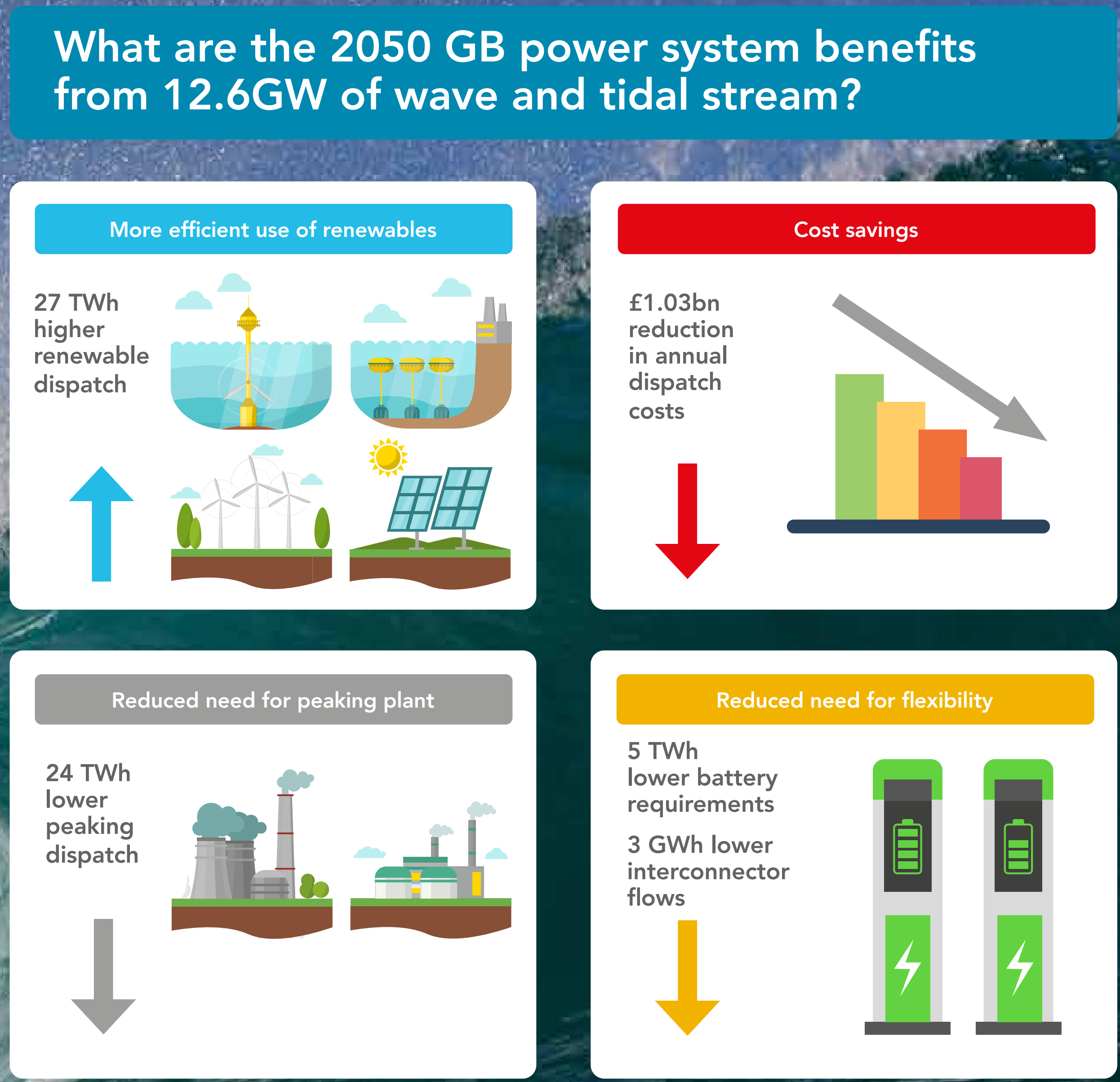
The results of this study quantify the potential power system benefits, in terms of reduced dispatch costs, increased renewable dispatch and reduced storage and import requirements.

The results from this work can be summarised as:

- Energy planning modelling projects **6.4GW of wave** and **6.2GW of tidal stream** deployments in GB by 2050, if the SET Plan targets are reached by 2030.
- Previous work has shown that the resultant value to the UK economy from these deployments would be up to **£8.9bn Gross Value Added**.
- This study shows that the potential power system benefits of this 12.6GW deployment of marine energy would be up to **£1.03bn reduction in dispatch costs per annum**.
- This cost reduction comes from **a higher dispatch of renewable energy** – by up to 27 TWh (+6%), and thus **a lower requirement for expensive peaking generation** – by as much as 24 TWh (-16%) when wave and tidal generation are part of the electricity mix, compared with a scenario without marine energy generation.
- Additionally, the scenario which includes marine energy demonstrates a higher ability to meet domestic (GB) demand with domestic generation, as it requires 5 TWh less (-65%) battery use and 3 GWh less (-6%) energy imports over interconnectors.
- Several sensitivity analyses have also been performed, and it has been found that the general trend in results is consistent between every sensitivity scenario, that is: **a higher penetration of marine energy results in lower dispatch costs, higher renewable dispatch, lower peaking generation and f lexibility requirements**.

These results highlight the significant potential value to the GB power system, if the government invests in the development and deployment of marine energy technologies. These technologies still need focused investment to enable the reduction of LCOE through performance improvement, cost efficiencies and supply chain development.

WHAT ARE THE UK POWER SYSTEM BENEFITS FROM DEPLOYMENTS OF WAVE AND TIDAL STREAM GENERATION?



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