Department for Business, Energy & Industrial Strategy

Offshore Wind Evidence + Change Programme

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ARUP

CATAPULT Offshore Renewable Energy

ABP mer

Future Offshore Wind

Future offshore wind scenarios: an assessment of deployment drivers

April 2022

Enter

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Client Foreword

The Climate Change Committee (CCC) estimates that we may need up to 140GW of offshore wind to reach net zero by 2050, compared to around 11GW operating today. Enabling this scale of increase would require a significant amount of seabed across the UK, requiring judgements about how we best manage the various demands on our marine environment.

In this context, the Department for Business, Energy & Industrial Strategy (BEIS), The Crown Estate and Crown Estate Scotland commissioned Arup to undertake this study into offshore wind deployment. The aim was to better understand the spatial implications of the deployment potential needed to meet net zero. This report, and the associated interactive web tool, provide an initial evidence base for the many stakeholders that have a role or interest in securing the UK's clean energy future, in balance with the environment, and other marine industries, such as shipping and fishing. The report does not constitute a marine spatial plan.

In undertaking the study, Arup has modelled illustrative spatial scenarios for offshore wind development out to 2050. These investigate the potential implications for future relative deployment costs and offshore wind technology choice, in interaction with the environment, and other marine infrastructure and industries. The resulting output has enabled a more holistic consideration of the complex interactions concerning offshore wind deployment out to net zero than has been previously undertaken.

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The report sets out the specific methodology used, in addition to the assumptions which underpin the key considerations and recommendations. This provides an opportunity to reflect on how to approach consideration of the spatial and cost implications of deploying sufficient offshore wind to meet net zero. We will continue to work with policymakers, industry, and broader stakeholders as we share the findings of this work and explore how, together, we can deliver further offshore wind deployment.

The project has been delivered as part of The Crown Estate's Offshore Wind Evidence and Change programme which seeks to facilitate the sustainable and coordinated expansion of offshore wind to help meet the UK's commitments to low carbon energy transition whilst supporting clean, healthy, productive, and biologically diverse seas.

This study is a significant addition to the evidence base informing the future outlook for the offshore wind sector and illustrates the importance of working collaboratively in addressing how we can best manage our marine environment in the context of increasingly busy seas. The insights gained from the project will inform current initiatives such as The Crown Estate's Offshore Wind Evidence and Change programme and UK Government's Marine Spatial Prioritisation Programme which are gathering further data and building evidence, using this study as an important reference point.

Executive summary

The UK has ambitious objectives for the role of offshore wind in reaching net zero by 2050. To realise them, deployment must increase from approximately 10GW of installed capacity in the last decade to 40GW by 2030, and potentially up to 140GW by 2050. These future offshore wind farms will add to the many other uses of UK territorial waters and the wider UK continental shelf, and it is crucial to understand the complex interactions between them.

Arup, alongside the Offshore Renewable Energy (ORE) Catapult and marine consultancy ABPmer, were appointed by the UK Government's Department for Business, Energy & Industrial Strategy (BEIS), The Crown Estate, and Crown Estate Scotland to research a range of scenarios to explore:

- **The complex interactions** between offshore wind, different activities in our seas and protection of the marine environment
- **The influence on relative levelised cost of energy (LCOE)** of different future decisions
- **The role of floating** wind.

The outcomes do not present a plan or recommendation for the future spatial development of offshore wind or other activities in UK waters; instead it presents multiple outputs that demonstrate, within agreed parameters, the impact different decisions and system changes could have on the location and relative cost of the offshore wind portfolio required to deliver net zero by 2050. This study was intended to provide an objective and comprehensive evidence base to support future decision-making. When reviewing the output from the analysis, it is important to take into account the limitations of the modelling.

There are several factors outside the scope of this study such as assessment of: onshore grid capacity constraints; unknown environmental impact of a large concentration of wind farms in a particular seabed area; unknown impacts on particular environmental features or species; installation and operational considerations; wake effects across multiple wind farm clusters; air defence radar and the extent of CCS deployment; resilience and spread of supply regionally; and regional supply chain capability. The selected bounding parameters were discussed and agreed through significant industry stakeholder engagement at key points within the project, and confirmed by BEIS, The Crown Estate, and Crown Estate Scotland.

Deployment is based on 1GW windfarms and does not consider deployment of smaller sized projects in UK waters, for which there is also great potential, particularly in locations such as Northern Ireland and other coastal locations where smaller sites could be developed in balance with other considerations.

A vast range of future outcomes

We modelled over 700 unique permutations to explore different assumptions and uncertainties. The 190 final model runs can be accessed through an interactive dashboard at

www.futureoffshorewindscenarios.co.uk

Changing assumptions on a broad range of geospatial and system factors produced significant diversity in the potential spatial distribution of offshore wind in increasingly busy UK waters.

Executive summary

Factors tested included: geospatial factors (human and environmental) and system factors (technology learning rates for fixed and floating offshore wind, grid system charging models, production of hydrogen, and funding approaches). Figure 1 represents the full range of outputs of the analysis presented as a heat map, showing areas frequently featuring in the model outputs alongside the wide variability in possible deployment locations.

- Active NSTA Platforms
- Wind Site Agreements
- Wind Leasing Round 4 Preferred Projects
- Nuclear Power Stations (10km buffer)
- IMO Traffic Sep. Schemes
- Navigational Dredging
- CAA Airports (10km buffer)
- Minerals Aggregates Site Agreements (1km buffer)
- Tidal Stream Site Agreements (5km buffer)
- Natural Gas Storage Site Agreements
- Carbon Capture and Storage Site Agreements
- Open Dredge Disposal Sites
- Crown Estate Scotland Energy Sites
- Coastal firing ranges
- Floating Offshore Wind Test and Demo Sites

Count of scenarios per cell

- 1 - 8
- 9 - 23
- 24 - 44
- 45 - 73
- 74 - 117

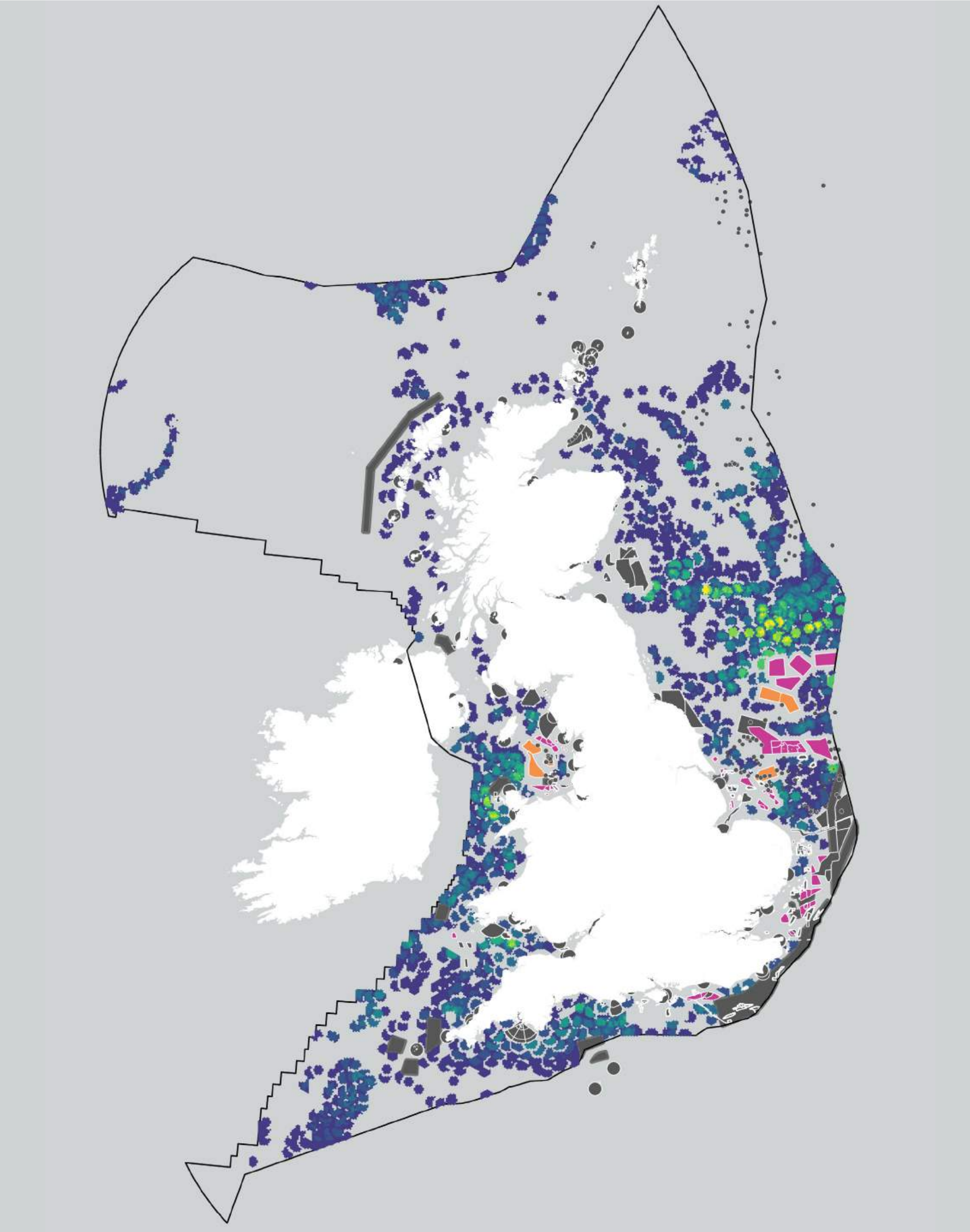


Figure 1.

Heat map showing potential deployments in all modelled outcomes. Geospatial factors treated as hard in all scenarios are outlined in grey for reference, and offshore wind leasing sites in orange and pink (excluding ScotWind leasing sites). Cell colour represents the frequency with which that cell is deployed across all scenarios, ranging from dark blue (least frequent) to yellow (most frequent).

Balancing spatial planning priorities

The approach to balancing seabed uses has significant potential for affecting the cost of delivering offshore wind.

Shipping, fishing, and sensitive seabird foraging areas have the greatest influence, due to their significant interaction with offshore wind and their large spatial distribution.

The highest-cost portfolios see offshore wind developed in more remote sites to minimise interactions with sensitive geospatial factors.

The range of future outcomes identified a 70% difference in average LCOE from the lowest to the highest modelled scenarios.

Executive summary

The role of floating wind

Floating technologies could open up more seabed, increasing options in spatial planning and enabling development in areas that have less overlap with sensitive marine areas and other activities, although there are equally unknowns about the potential impact of these technologies.

The modelling considers price parity with fixed foundation to be a possibility from the late 2030s, when floating offshore wind could play an increasingly significant and potentially dominant role. However, the recent Scotwind leasing round offer results, included over 14GW of floating wind, indicating there could be a sufficient number of projects to help drive down costs and achieve parity with fixed-bottom windfarms earlier. Increasing the level of floating wind does not necessarily cause a direct increase in portfolio LCOE as this is influenced by other factors, such as distance from shore.

Influence of wider system factors on LCOE

The modelling highlighted the important influence of network charging on the geospatial distribution and portfolio cost of offshore wind.

We explored the effects of removing the locational component of charges by setting transmission network use of system (TNUoS) charges to zero across all grid charge zones. Noting that this leads to system level costs that are then unaccounted for in the modelling, it produces wider geographical distribution across most scenarios, although the variation is less obvious where there are other dominant geospatial factors.

The study has highlighted:

The need for whole-system planning and integrated marine spatial planning.

Policy and marine spatial planning decisions would influence the cost of and ability to achieve 140GW offshore wind, with the highest-cost scenario portfolios seeing deployment in more remote offshore sites.

To achieve significant growth in offshore wind at an acceptable cost, policy decisions must consider other activities in our seas, alongside protecting the marine environment. Decisions about areas defined for shipping, fishing and seabird foraging are likely to be the most influential in determining what a 140GW UK portfolio will look like in 2050.

Industry support and collaboration could achieve faster floating wind learning rates and provide broader, cost-competitive spatial options sooner, but technological aspects alone are unlikely to provide the answer to balancing the multiple complexities.

Decisions about the UK's transmission network will influence the deployment, and cost, of offshore wind and the UK's net zero energy portfolio. Choices about how, where and when coordinated offshore networks are located could reduce LCOE in locations close to coordinated infrastructure. Understanding the influence of a coordinated approach, through whole system planning, will need to be iterative, reflecting the way that deployment locations inform transmission design and transmission design informs deployment cost and location.

Financial support mechanisms create an environment that encourages investment, and the research shows how investor confidence can result in lower LCOE through cheaper financing by assessment of a higher sensitivity of Weighted Average Cost of Capital.

Next steps:

Using this evidence base to inform approaches in the Department for Environment, Food & Rural Affairs (Defra) Marine Spatial Prioritisation programme and support general discussion with devolved marine planning authorities, aiding the next steps taken towards whole-system planning, potential prioritisation of activities and integrated marine spatial planning.

Continuing to develop the evidence base through:

- Integration and assessment of broader system factors, including work by others as part of the Offshore Transmission Network Review (OTNR).
- Establishing more detailed datasets and evidence base in key areas, such as sensitive seabird foraging areas and CCS.
- Assessing and discussing in more detail the balance of different levels of activity of fishing, shipping and seabird foraging, as well as other geospatial factors, alongside continued stakeholder engagement.

1. Introduction

1. Introduction

1.1 Purpose of this study

Arup, alongside ORE Catapult and marine consultancy ABPmer, were appointed by the BEIS, The Crown Estate and Crown Estate Scotland to research a range of scenarios to explore the UK's future offshore wind portfolio.

This report provides an evidence base that can be used by policymakers, offshore wind developers and industry stakeholders to explore:

- **The complex interactions** between offshore wind, different activities in our seas and protection of the marine environment
- The **influence on relative LCOE** of different future decisions
- The **role of floating** wind.

The outcomes of this analysis are subject to the key bounding parameters set by the study and agreed with BEIS, The Crown Estate, and Crown Estate Scotland. This includes the following fundamental assumptions and those set out in Section 2.2:

- The rate of offshore wind deployment is not bound by leasing, consenting, regulatory, consultee, or contracting timeframes, and these are the same for all offshore wind deployed in the model.
- The supply chain can deliver at the required deployment rate with no capacity or geographic restrictions.
- There are no explicit onshore grid capacity restrictions. However, we applied a 'density cap' to represent the limitations of a maximum wind farm density that could be deployed in a particular offshore region – noting that maximum wind farm density at a macro level is not well understood or defined and requires further work to establish.

This project is not a marine spatial planning exercise, which is recognised as a separate, complex, and changing process.

The outcomes do not present a recommendation for the future of offshore wind in UK waters. They demonstrate the potential geospatial spread and cost of a future offshore wind portfolio that targets net zero by 2050.

Arup has used a data-driven approach that illustrates the interactions between system and technology uncertainties, costs, and geospatial factors, within the bounding model parameters, and across multiple scenarios and sensitivities.

This project is part of the OWEC Programme led by The Crown Estate, together with its programme partners, BEIS and Defra.

1.2 Definitions

The report uses the following terms:

- **Pathway:** three net zero pathways set 2030 and 2050 targets for total offshore wind deployment, and deployment rates required to achieve these targets, based on three scenarios in the Climate Change Committee's *The Sixth Carbon Budget: The UK's path to Net Zero report*[3].

  The model starts at year 2034 from an assumed operational capacity of 55GW (based on the known pipeline in 2021, excluding ScotWind sites) and deploys offshore wind to the total capacity of the pathway.

  - Base Ambition: 65GW total capacity by 2050
  - Balanced Growth: 95GW total capacity by 2050
  - High Ambition: 140GW total capacity by 2050

- **Factor:** any factor other than offshore wind that influences either the LCOE or spatial distribution of future offshore wind. Examples include system factors such as learning rates or cost of transmission charges, and geospatial factors defined below.
- **Geospatial factor:** uses of the seabed other than future offshore wind deployment. These are incorporated into the model using geospatial layers to represent, for example, shipping lanes, designated sites, existing leasing areas, etc. More details about the geospatial factors included in the project are given in Section 2.2, and there is a full list of the input data sources in Appendix A.

1. Introduction

– **Scenario:** combination of geospatial factors treated either as 'hard' (no offshore wind deployment can occur in these areas), 'soft' (offshore wind deployment can overlap with these other seabed uses in the model but it is balanced against cost, noting this study does not investigate any potential impacts of overlaps), or 'not considered' (the layer is not included in the model). For a detailed explanation of the methodology, please refer to Section 2.1. For a detailed definition of the geospatial factors considered in each scenario see Appendix B.

– **Sensitivity:** variations in system-level factors that affect the LCOE of all locations in the model. We tested sensitivities relating to transmission charging, cost of capital, learning rates, hydrogen production and cluster density caps. As analysis progressed, a density cap was then applied across all scenarios and is a component of the final set of output scenario maps. Full details are given in Section 2.1.

– **LCOE:** levelised cost of energy is an industry-standard metric to compare the cost of generating electricity with the amount of energy produced. It includes all components across the life cycle of a wind farm, including development (DEVEX), capital (CAPEX), operational (OPEX) and decommissioning (DECX).

– **Portfolio LCOE:** the average LCOE across the deployed offshore wind capacity in the model. For example, in the High Ambition pathway the portfolio LCOE would be the average across a further 85GW of offshore wind.

– **Normalised LCOE:** LCOE is generally discussed in normalised terms (where the lowest LCOE is returned to a figure of zero and the highest to a figure of one), as the LCOE figures in this study are appropriate for relative assessment only.

– **Normalised soft area:** a measure of how constrained a given spatial cell is. Specifically, it is the sum of soft geospatial factor coverage in the cell, divided by the soft geospatial factor coverage in the most constrained cell in a given model run.

– **Loss function:** the sum of normalised LCOE plus normalised soft area – giving a minimum value of zero and maximum value of two. This enables comparison of locations, optimising for the combination of lowest LCOE and lowest coverage of soft geospatial factors (having a loss function value of closest to 0).

– **Normalised loss function:** a normalised value for the loss function output returning a figure between zero and one.

– **Deployment model:** an optimisation algorithm designed to deploy offshore wind to minimise the average 'loss function'. The output shows the locations the model has chosen to deploy offshore wind to meet the pathway target capacity.

– **Model run:** an assessment of deployment (including associated LCOE and geospatial distribution as outputs) for a given combination of 'Pathway', 'Sensitivity' and 'Scenario'. The modelling process and overview of how the combinations of 'Pathway', 'Sensitivity' and 'Scenario' interact to result in the model runs is shown in Figure 2.

A full list of the terminology used in this report can be found in the Glossary.

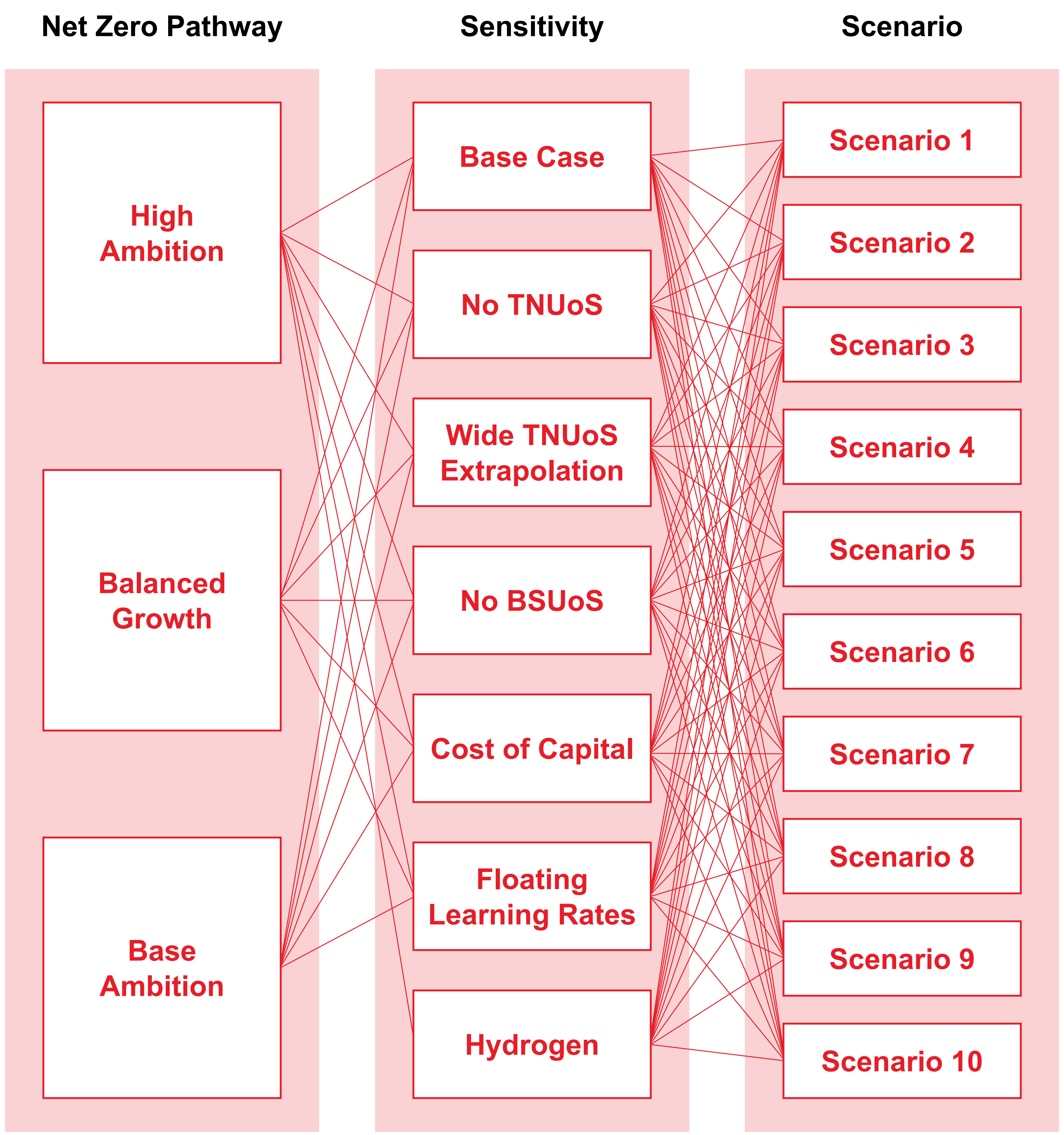


Figure 2.
Range of model runs assessed in the study, described in detail in Section 2.

2. Methodology

2. Methodology

2.1 Modelling approach

Our temporal and spatial modelling of the relative LCOE of offshore wind across UK waters through to 2050 identifies deployment locations that balance lowest LCOE with the lowest interaction with geospatial factors.

Offshore wind is deployed in the model over time to meet an annual target as set out by one of three net zero pathways to 2050[2]. Each pathway represents a different level of ambition for offshore wind deployment.

To capture the diverse and uncertain range of possible offshore wind scenarios, the modelling tested combinations of LCOE sensitivities and spatial scenarios. This resulted in hundreds of discrete model output runs that inform the key messages in this report. The full set of results can be viewed in the supporting project dashboard referenced in Section 7.

Our model divided the waters within the model boundary, set as the UK Exclusive Economic Zone (EEZ), into 2.5km diameter hexagon cells (Figure 3) and carried out calculations for each cell.

The bounding parameters were discussed and agreed through stakeholder engagement at key points within the project, and with the client group of BEIS, The Crown Estate and Crown Estate Scotland. More details about the engagement process are given in Section 2.4.

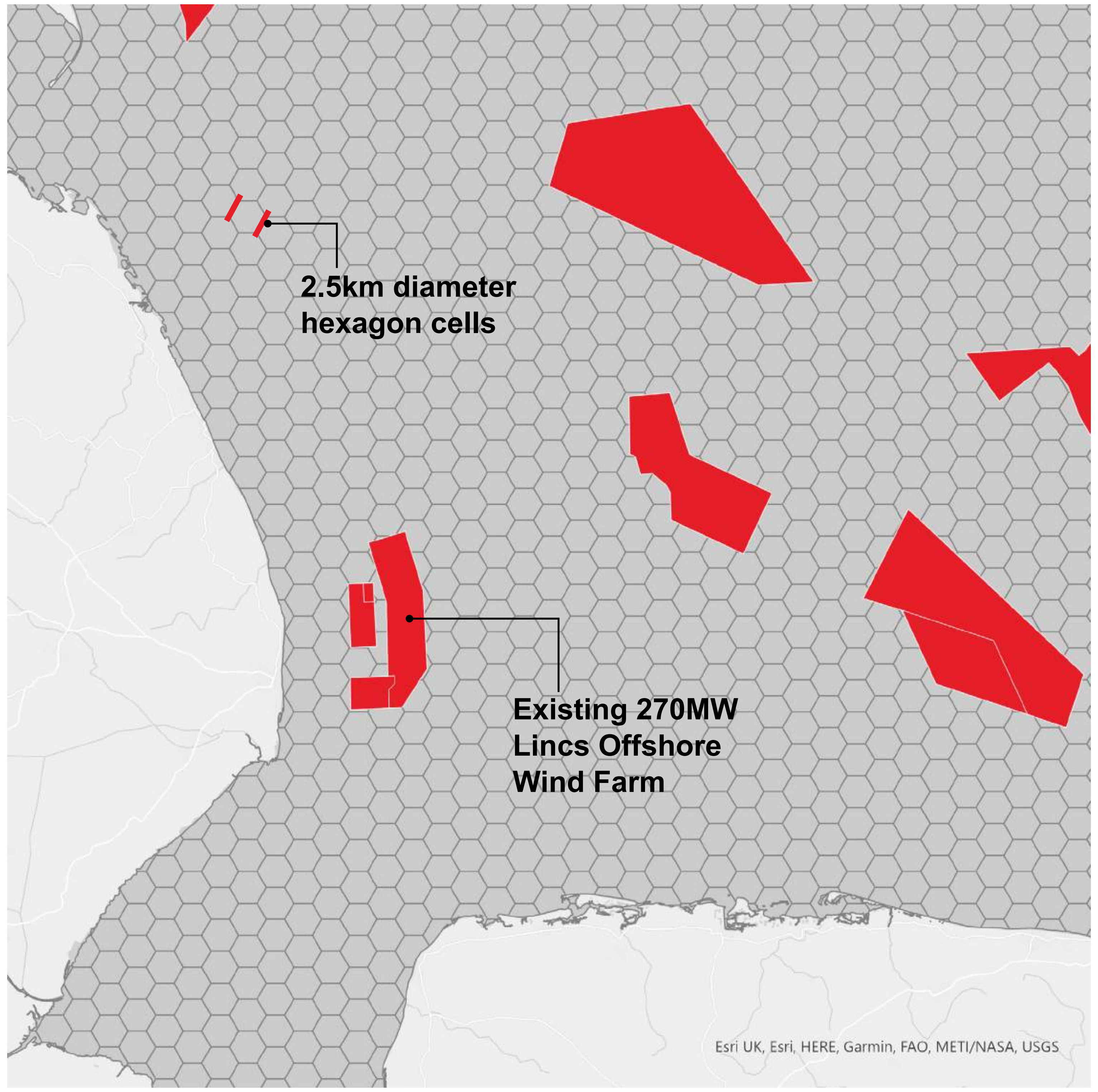


Figure 3.
The UK EEZ model boundary was divided into 2.5km hexagon cells

Net zero pathways

To provide a frame for the analysis, we defined three net zero pathways that contribute to the broader UK net zero ambition. The pathways set 2030 and 2050 targets for total offshore wind deployment as well as the deployment rates required to achieve these targets.

- **Base Ambition:** 65GW total deployed capacity by 2050, achieved by delivering 40GW by 2030 at an average deployment rate of 3GW/year, followed by a slowing of deployment rate from 2030 to an average of 1GW/year.
- **Balanced Growth:** 95GW total deployed capacity by 2050 achieved through an average deployment rate of 3GW/year from 2020 to 2050.
- **High Ambition:** 140GW total deployed capacity by 2050, achieved by delivering 40GW by 2030 at an average deployment rate of 3GW/year, followed by ramping up to an average deployment rate of 5GW/year between 2030 and 2050. This pathway assumes a proportion of the total capacity is non-networked offshore wind dedicated to hydrogen production.

These pathways reflect the maximum range of offshore wind deployment presented in the Climate Change Committee's *The Sixth Carbon Budget: The UK's path to Net Zero*[3]. The full literature review on which the pathways selected for this project was based is set out in detail in the *Net Zero Pathways report*[2].

2. Methodology

All pathways assume the existing project pipeline is built and operational by 2034, considering known or expected timeframes for operation of leased projects. The recently awarded ScotWind option agreement offers are not included in the existing pipeline. Beyond projects currently in construction, consented, and leased at the time of project commencement in January 2021 (totalling 18GW), we assumed that a further 22GW of the broader potential pipeline will be delivered by 2030, achieving the 40GW target across all pathways. The pathways therefore only differ in deployment rate and total capacity beyond 2030 as illustrated in Figure 4.

The model starts deploying offshore wind up to the total target capacity of the pathway beyond 2034 and the 55GW capacity assumed to be operational at this date (based on the known pipeline in 2021, excluding Scotwind sites).

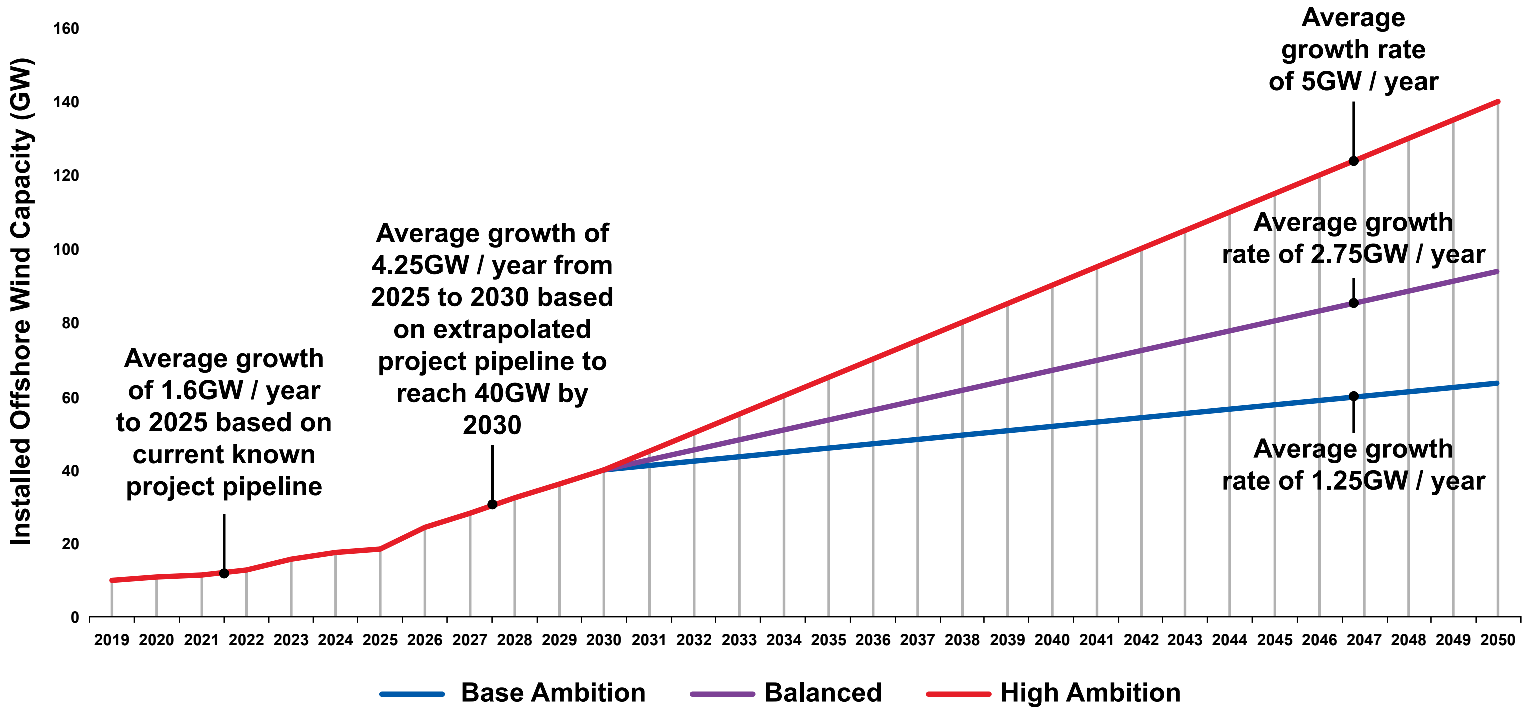


Figure 4.

Smoothed offshore wind deployment against time for each pathway, building from delivery of 40GW in 2030[2].

Levelised Cost of Energy

Figure 5 captures the different components included in the calculation of LCOE, an industry-standard metric to compare the cost of generating electricity with the amount of energy produced.

The costs include all components across the life cycle of a wind farm, including development (DEVEX), capital (CAPEX), operational (OPEX) and decommissioning (DECX). Details of the assumptions for this study are given in Section 2.2.

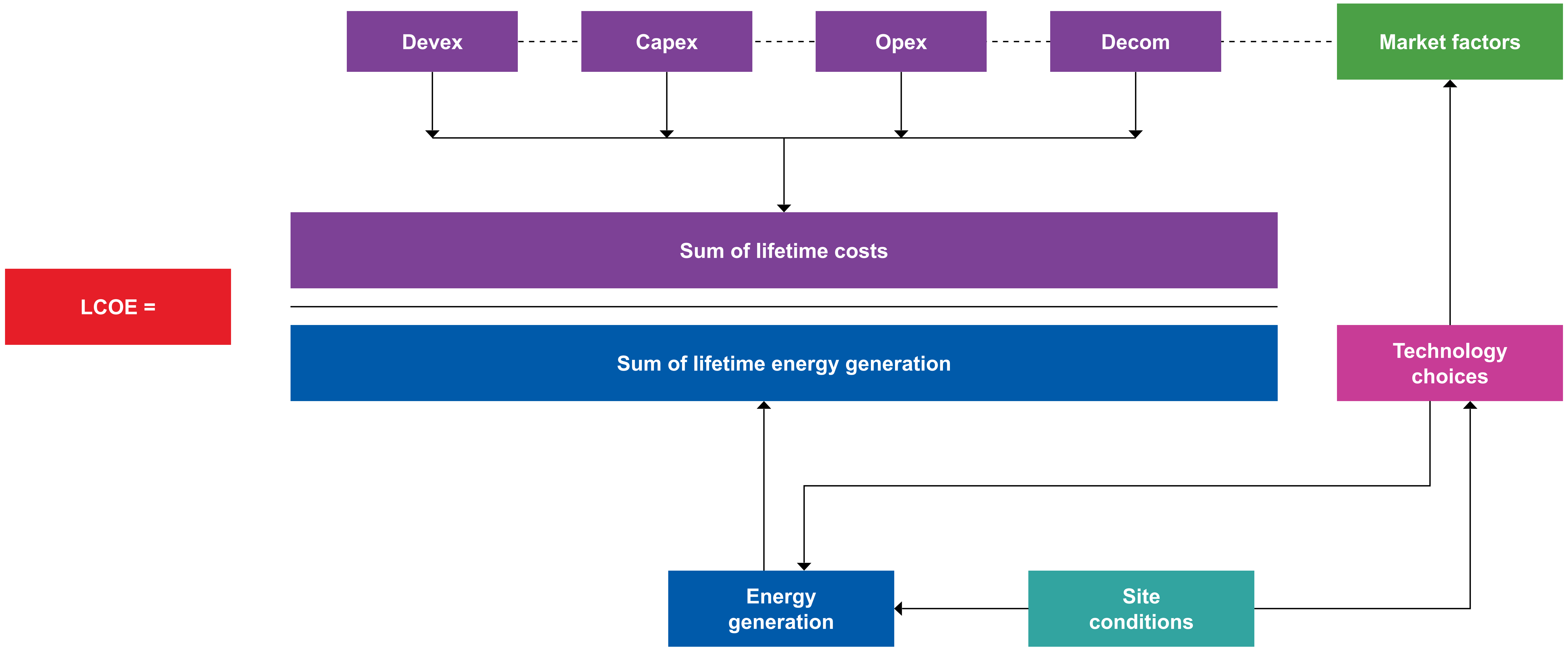


Figure 5.

Components of an LCOE calculation.

2. Methodology

The model generates values for the relative LCOE of offshore wind in all hexagon cells considering both fixed and floating foundations. The output costs are based on a 1GW project with site parameters defined by those associated with each hexagon cell. The model doesn't allow for smaller projects, which could also have ample opportunity around the UK, particularly in smaller pockets of waters with potential for deployment.

For each year from 2034 to 2050, relative LCOE values in £/MWh are calculated for all cells in the UK EEZ that do not overlap with hard geospatial factors (as defined opposite).

These values are then normalised using the minimum and maximum LCOE values for each year. The cell with the lowest LCOE value within a given year has a normalised LCOE value of zero, whereas the cell with the highest LCOE value has a normalised value of one.

LCOE sensitivities

To understand the impact on the cost and location of offshore wind, we tested six system-level sensitivities that would affect the relative LCOE results across the whole of the UK (in addition to a **Base Case LCOE run** detailed in Section 2.2):

1. **No TNUoS:** removing network transmission charges to level the current differential costs between regions (noting there would be system-level costs that are then unaccounted for in the modelling).
2. **Wide TNUoS extrapolation:** extending ESO's five-year forecast trends for network transmission charges to increase the regional differences.
3. **No BSUoS:** removing the cost component associated with network balancing charges.
4. **Cost of capital:** removing Contract for Difference mechanism, resulting in a knock-on effect on the Weighted Average Cost of Capital of the project.
5. **Floating learning rates:** reducing the learning rate for floating wind costs to match the current learning rate for the more mature industry of fixed offshore wind.
6. **Hydrogen:** dedicating 40GW of the electricity produced by offshore wind farms to producing green hydrogen (only tested on the 140GW High Ambition pathway).

Geospatial factors

The model includes datasets relating to the distribution of features that could influence the location of offshore wind farms. These provided a starting point for identifying areas with potentially lower presence of geospatial factors and for understanding how implementing different scenarios might affect environmental and socio-economic receptors.

Environmental

- Special Protected Areas
- Special Areas of Conservation
- Marine Conservation Zones
- Marine Protected Areas
- Sites of Special Scientific Interest
- Ramsar areas
- Seabird foraging ranges

Infrastructure

- Existing renewable energy lease areas
- Oil and gas platforms
- Cable and pipe agreements
- Natural Gas and Carbon Capture and Storage lease areas
- Marine archeology
- Marine Mineral license areas

Other Industries

- Fishing areas
- Traffic separation schemes
- Anchorage areas
- Shipping lanes
- Recreational navigation channels
- Military practice areas
- Helicopter routes
- Airports and air navigation radar
- Nuclear power stations
- Dredge sites and disposal areas

Figure 6.
Geospatial factors included in the modelling.

2. Methodology

The geospatial datasets in Figure 6, detailed fully in Appendix A, could be treated as either 'hard', 'soft' or 'not considered' in each model run:

- **Hard:** If a cell has any overlap with a GIS layer classified as hard, it is flagged in the model and excluded from the deployment model for that particular run.
- **Soft:** The model calculates the area of overlap between a cell and a GIS layer classified as soft. This is repeated for all layers selected as soft, and then summed together to give a total overlap area for each cell, which could be greater than the total cell area due to the presence of various overlapping geospatial factors. The model tries to avoid these factors when looking for locations to deploy offshore wind clusters, deploying in locations with lowest combined LCOE and soft area based on the normalised loss function, noting this study does not investigate any potential impacts of overlaps.
- **Not considered:** GIS layers set to have no impact on the analysis and are excluded in the model run.

Refer to Table 1 for a definition and description of each scenario modelled.

Deployment model

The deployment model identifies the most favourable areas for deployment of offshore wind between 2034 and 2050 for each scenario modelled. The outputs are based on the input assumptions (detailed in Section 2.2) agreed following consultation with the wider industry.

The location of offshore wind deployment optimises for the lowest relative LCOE and the lowest interaction with geospatial factors by minimising the loss function. This output is shown in the form of 1GW clusters which target a total deployment over time. In reality, other locations could be selected beyond the deployed clusters in the model.

The analysis was run for all combinations of net zero pathways, LCOE sensitivities and geospatial scenarios as illustrated in Figure 2 (except for the hydrogen sensitivity which was only run for the High Ambition pathway), resulting in a total of 190 runs.

The analysis was run for all combinations of net zero pathways, LCOE sensitivities and geospatial scenarios as illustrated in Figure 2 (except for the hydrogen sensitivity which was only run for the High Ambition pathway), resulting in a total of 190 runs.

Density cap

Following a review of the initial output, a method for capping deployment density was established. The total 190 final modelled scenarios and figures presented in this report include this density cap (unless stated otherwise). They can be accessed through an interactive dashboard at

www.futureoffshorewindscenarios.co.uk

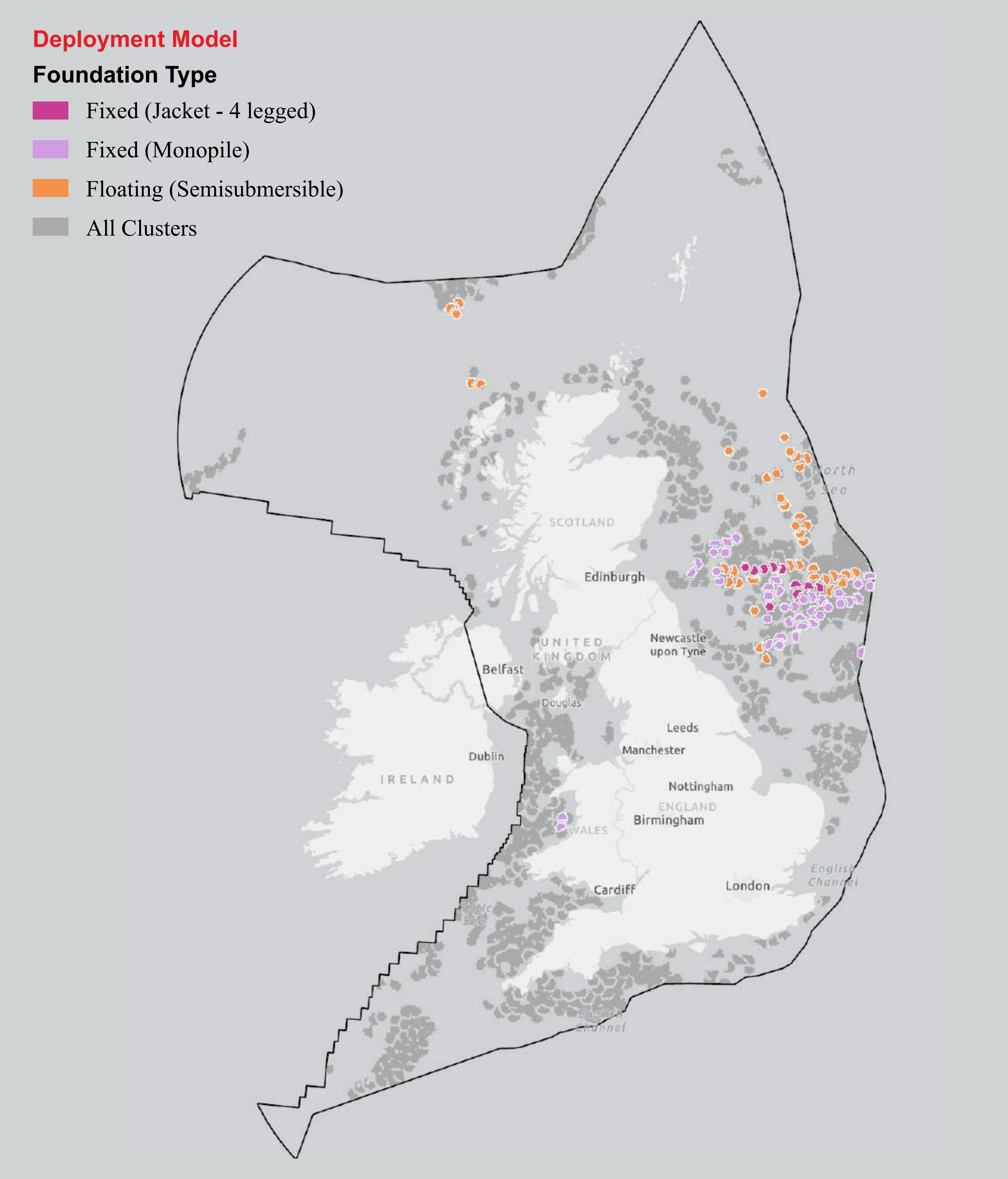
A density cap was introduced that limited the maximum number of offshore wind clusters that could be located within a certain radius of other clusters that had already been deployed.

This density cap is used as a proxy to represent the real-life factors that would limit the concentration of offshore wind farms in a particular region of seabed.

These factors include onshore grid capacity constraints; unknown environmental impact of a large concentration of wind farms in a particular seabed area; installation and operational considerations; wake effects across multiple wind farm clusters; resilience and spread of supply regionally; regional supply chain capability. While the density cap was introduced as a proxy for these real-life factors, it is a model simplification of many complex topics and only goes so far towards representing them.

Figure 7 shows example output in the form of the deployment model for the 'without' and 'with' density cap sensitivity. The deployment map images show the combined output from all modelling runs as grey clusters in the background.

2. Methodology



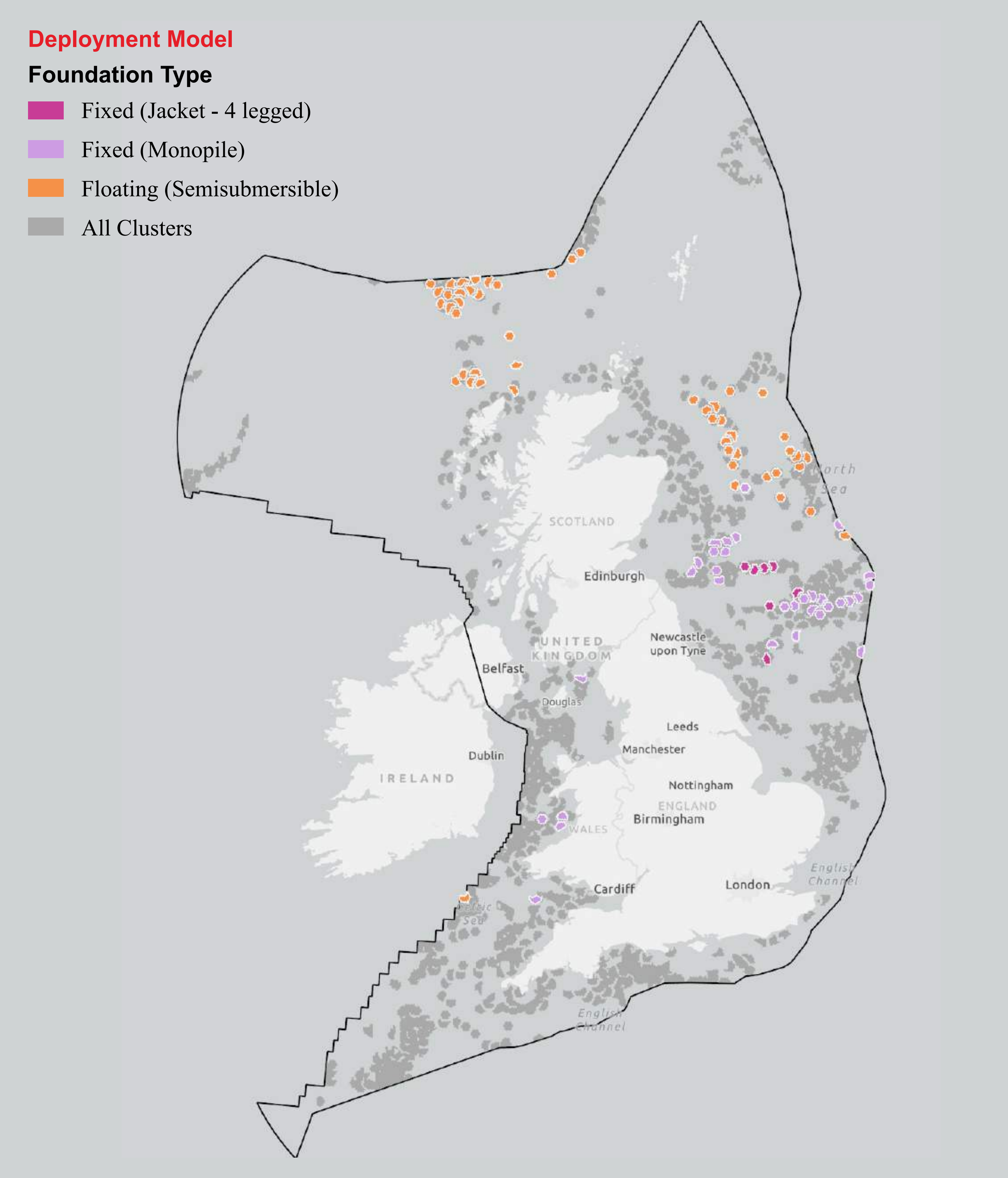


Figure 7.
Deployment maps showing the dispersion effect on deployed clusters of applying the density cap (right) compared with no density cap (left) (No TNUoS Sensitivity, Scenario 7)

2. Methodology

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Description	All factors – apart from those that are always treated as hard – are not considered, so cost is the sole driver of cluster locations. This scenario reflects the lowest bound on cost to deploy offshore wind if spatial interactions were not a necessary requirement.	A 13km coastal buffer is introduced as hard. All factors that individually impact LCOE by less than 2% are treated as soft to test their influence in combination, and to understand the cumulative cost impact of apparently less significant factors. All other factors are not considered.	A 13km coastal buffer is maintained as hard. Environmental designations are set to soft, with all others set to not considered. This scenario provided clarity on the impact on LCOE and the interfaces with designated sites when prioritising the desire to avoid offshore wind deployment in environmental designations.	A 13km coastal buffer is maintained as hard. Environmental designations are set to hard, with all others set to not considered. This was used to understand the influence on LCOE of completely avoiding environmental designations.	A 13km coastal buffer is maintained as hard. All environmental designations and those factors that were shown to individually impact LCOE by less than 2% are treated as soft. In addition, the largest spatial extent of fishing, shipping and seabird foraging are treated as soft. This scenario was used to understand the impact on LCOE and location of balancing the three most influential geospatial factors, alongside a wider set of more limited footprint factors.
Hard geospatial factors In addition to those factors that are always treated as hard, as listed in Section 2.2	None	13km coastal buffer	13km coastal buffer	13km coastal buffer Special Protected Areas (SPA) + 5km buffer Special Areas of Conservation (SAC) Marine Conservation Zones (MCZ) Marine Protected Areas (MPA)	13km coastal buffer
Soft geospatial factors	None	All factors that have <2% influence on LCOE individually as detailed in Section 2.2	Special Protected Areas (SPA) + 5km buffer Special Areas of Conservation (SAC) Marine Conservation Zones (MCZ) Marine Protected Areas (MPA)	None	Fishing (100% landed value) Shipping (200 transits per year + 3.5 nautical mile buffer Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA) All factors that have <2% influence on LCOE individually as detailed in Section 2.2

Table 1.
Description of the scenarios and treatment of geospatial factors for each.

2. Methodology

	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Description	To understand the individual impact of limiting co-existence with fishing, scenario 5 was replicated but with the fishing areas treated as hard.	To understand the individual impact of limiting co-existence with shipping, scenario 5 was replicated but with shipping activity treated as hard.	To understand the individual impact of limiting co-existence with environmental designations and seabird foraging areas, scenario 5 was replicated but treating those layers as hard.	To understand the impact of imposing a larger coastal buffer, scenario 5 was replicated using 40km instead of 13km as hard.	In this upper bound case, a 13km coastal buffer, environmental designations and seabird foraging, fishing, and shipping are treated as hard. All other factors are treated as soft. This scenario will help understand the extreme extents of cost impacts if other activities and protection of marine environments are prioritised over offshore wind.
Hard geospatial factors In addition to those factors that are always treated as hard, as listed in Section 2.2	13km coastal buffer Fishing (100% landed value)	13km coastal buffer Shipping (200 transits per year + 3.5 nautical mile buffer	13km coastal buffer Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA)	40km coastal buffer	13km coastal buffer Fishing (100% landed value) Shipping (200 transits per year + 3.5 nautical mile buffer Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA) All factors that have <2% influence on LCOE individually as detailed in Section 2.2
Soft geospatial factors	Shipping (200 transits per year + 3.5 nautical mile buffer Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA) All factors that have <2% influence on LCOE individually as detailed in Section 2.2	Fishing (100% landed value) Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA) All factors that have <2% influence on LCOE individually as detailed in Section 2.2	Fishing (100% landed value) Shipping (200 transits per year + 3.5 nautical mile buffer All factors that have <2% influence on LCOE individually as detailed in Section 2.2	Fishing (100% landed value) Shipping (200 transits per year + 3.5 nautical mile buffer Seabird foraging (medium risk) Environmental designations (SPA + 5km, SAC, MCZ, MPA) All factors that have <2% influence on LCOE individually as detailed in Section 2.2	None

Table 1 (continued).
Description of the scenarios and treatment of geospatial factors for each.

2. Methodology

2.2 Critical assumptions - sensitivities explained

Levelised cost of energy

The LCOE calculation methodology has been developed specifically for this strategic-level study and the results should not be relied upon for other purposes outside of this context.

The costs are based on a spend profile that follows an assumed UK offshore wind farm project timeline shown in Figure 8.

The relative LCOE calculations are based on the lowest-cost solution for each location, considering fixed and floating foundations: steel monopiles, three- and four-legged piled jackets, concrete gravity bases and steel semisubmersibles. The cost estimates account for:

DEVEX costs cover development and consenting, engineering and certification, and surveys. For the purposes of this study, we assumed the same costs for all developments.

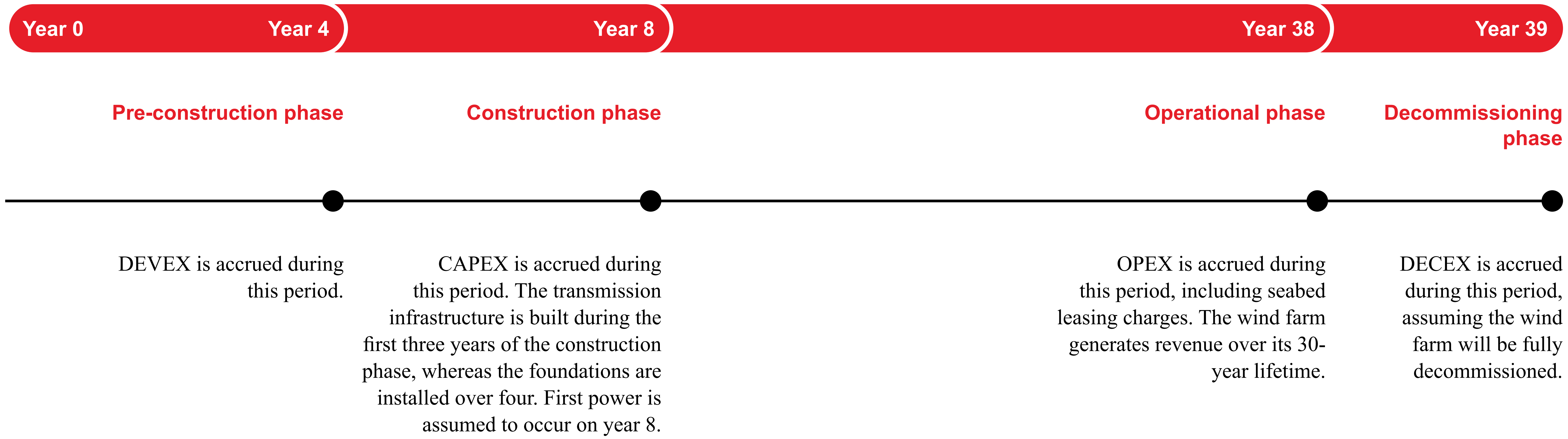


Figure 8.
Assumed project timeline.

CAPEX costs include fabrication, transport and installation of the turbines, foundations, and wind farm transmission infrastructure (array cables, substation and export cables). The foundations are based on concept-level designs that vary depending on site-specific conditions such as water depth, seabed composition and metocean conditions, as well as the turbine size.A maximum feasible water depth was assumed that excluded areas in the North, North West and South West of the UK EZZ boundary. Turbine sizes are assumed to increase to 20MW from 2029 onwards. Installation is based on selected ports in the UK and mainland Europe identified as suitable for offshore wind construction and includes weather downtime.

Transmission infrastructure costs are based on the distance between the wind farm and the nearest primary onshore substation. For wind farms closer than 100km, a High Voltage Alternating Current (HVAC) transmission system, costs and electrical cable losses are assumed; for wind farms further away, High Voltage Direct Current (HVDC) is assumed.

Costs related to insurance, contingency and project management are also considered.

OPEX costs include maintenance associated with major, minor, and preventive repairs and are estimated using the nearest suitable UK maintenance port. The model selects either a Crew Transfer Vessel (CTV) or Service Operation Vessel (SOV) maintenance strategy, depending on the site-specific metocean conditions and distance to port.

The Balancing Services Use of System (BSUoS) charge is the same for generators in all locations. We ran a modelling sensitivity with this charge removed from the costs.

2. Methodology

The TNUoS charge depends on where in the country a generator is connecting to the grid – designed to reflect the cost to the transmission system of generators connecting in different locations. TNUoS costs are higher in zones which are further from the centre of load, such as Scotland..

Transmission costs are calculated based on the location of the onshore substation the wind farm is connected to. The analysis considered the 27 grid charge zones defined by National Grid Electricity System Operator (ESO)[7], plus an additional zone for Northern Ireland, and assumed each cluster connects radially through export cables directly to the closest onshore substation.

The study does not explicitly include any capacity restrictions at the onshore substations so as not to restrict offshore deployment artificially. The continued deployment of offshore wind will necessitate upgrades of the onshore grid.

The base case model uses the wider-tariff component of ESO's March 2021 five-year forecast in each zone and keeps this constant in each future modelling year. The local circuit tariff is simply treated as a CAPEX element. We modelled two additional sensitivities: the first removed TNUoS charging, and the second considered a wide extrapolation case where after the five-year forecast the TNUoS is extrapolated to represent ever-diverging charges that follow current trends.

In the case of Northern Irish waters where the equivalent TNUoS charges, TUoS, are determined on an individual generator basis, an approximation has been made for the purposes of this study. All cells in Northern Irish waters incurred equal transmission charges.

An average TNUoS charge was calculated for the year 2021 based on all the published generator facility charges[9]. The cost profile was assumed to follow the trends of the UK average, considering all grid charge zones for both the base case and wide range extrapolation case. BSUoS charges for Northern Ireland were assumed to be the same as the rest of the UK.

Costs also include seabed leasing charges based on the location of the wind farm, as well as insurance.

DECEX costs assume full decommissioning of the wind farm cluster after 30 years of operation, involving the de-installation of foundations, turbines, and substations.

LCOE is estimated considering all the costs above and the lifetime energy generated based on the Annual Energy Production (AEP), which is driven by the selected turbine power curve and estimated wind conditions at the site. AEP and LCOE are only valid for relative comparison between locations for this study and cannot be relied on for forecasting purposes.

This study considers cost of capital as the weighted average cost of capital (WACC) applicable to financing UK offshore wind projects. All values modelled and quoted for are in real terms, consistent with the basis of the cost estimations. A simple financing structure is assumed, where the key components are cost of equity, cost of debt and the mix of equity and debt used to finance a project.

The Base Case assumes that Contract for Difference mechanisms are in place to support the financing, as has been the case to date. We analysed a system sensitivity by including the effects of removing CfD support in the WACC for fixed and floating wind.

The model captures changes in future costs due to precedent either within the technology, or comparable technologies, using learning rates. Learning rates indicate the fractional reduction in the cost for each doubling of cumulative capacity. We applied these at a component level, based either on UK-only or global predicted deployment to 2050, and based either on total offshore wind deployment, or floating offshore wind deployment for technology-specific components.

In the Base Case, the learning rates for floating are assumed to reflect the rapid cost reduction experienced by fixed foundation offshore wind farms over the past decades. We carried out a system sensitivity to understand the effect of lowering the learning rates specific to the floating wind cost components to match the rates predicted for fixed technologies.

Hydrogen associated costs are included in the model runs for that sensitivity. In addition to calculating LCOE, the model estimates an equivalent levelised cost of hydrogen (LCOH) that accounts for the components used during the electrolysis process, either offshore or onshore. In the case of offshore electrolysis, upgrades to a conventional wind-only offshore substation to enable hydrogen generation are also considered, as well as substituting the export cable for a pipeline that connects to national hydrogen hubs, with assumed locations as shown in Figure 9.

Transmission charges are excluded for hydrogen; it is assumed that the hydrogen will be sold on to industrial users at these hubs. There is significant uncertainty around the cost of electrolysers and associated infrastructure for hydrogen production and further work to refine this could result in different outcomes.

2. Methodology

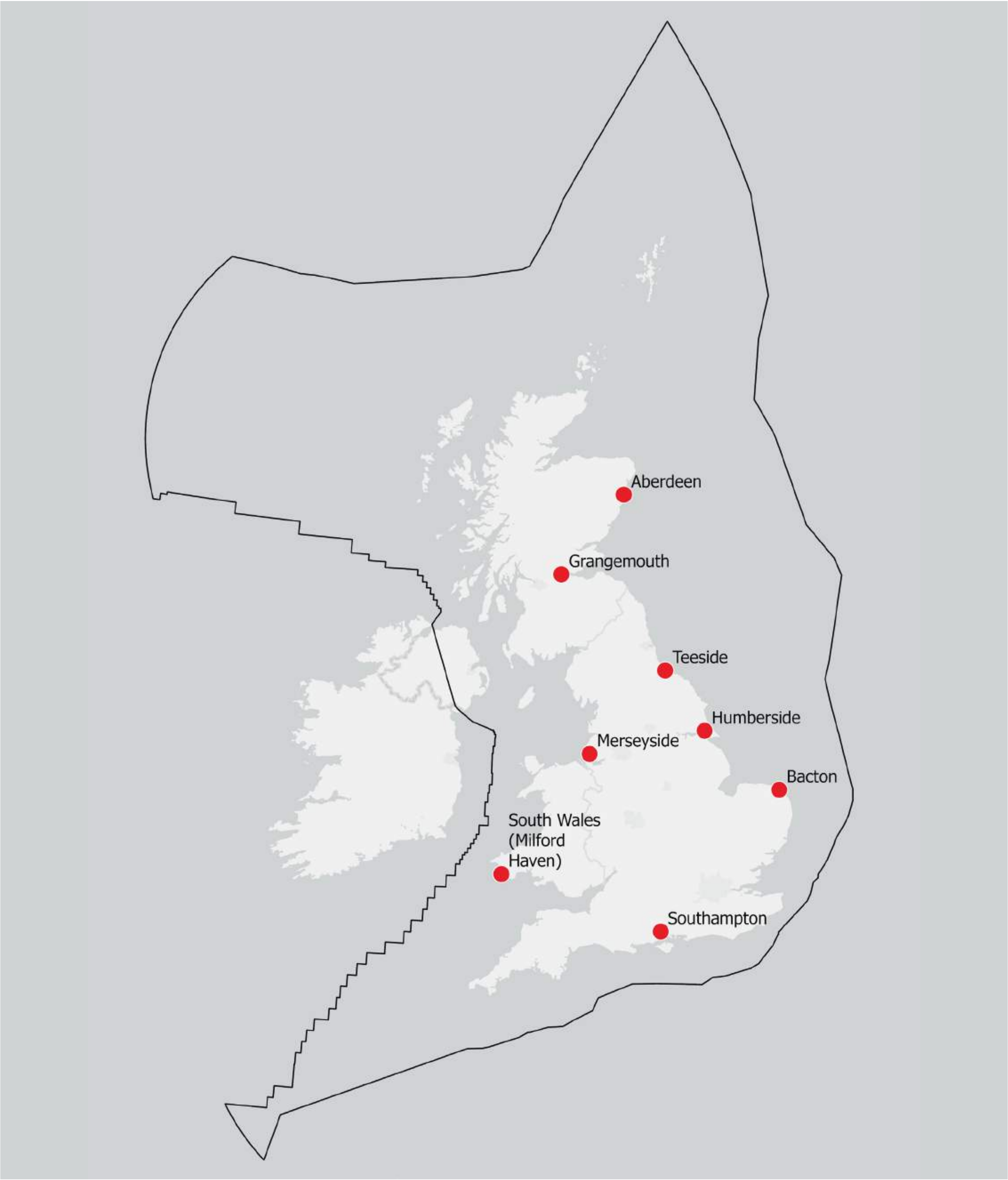


Figure 9.
Assumed location of onshore hydrogen hubs.

Geospatial factors
Further information on the following geospatial factors and associated datasets that were included in the modelling is provided in Appendix A.

Hard factors were applied to a subset of geospatial layers in Figure 10 throughout all the geospatial scenarios modelled, under the assumption that no offshore wind will realistically be able to co-exist with them. In the geospatial scenario runs, additional layers could be treated as hard, on top of factors that were always treated as hard:

- Existing site agreements for offshore wind, tidal, wave, natural gas storage, minerals, and aggregates, evaporites, and carbon capture and storage.
- Offshore wind Round 4 leasing sites, which were all assumed to be part of the pipeline that would be developed to 2034. At the time of the modelling, ScotWind option agreements had not been announced and were not treated as hard in the modelling.
- Floating offshore wind test and demonstration sites, primarily located in the Celtic Sea.
- Oil and gas platform locations.
- Nuclear power station outfalls.
- Aerodrome exclusion zones located on the coast.
- Navigational dredging channels.
- Dredge disposal areas.
- Military practice areas.
- Traffic separation schemes.

Soft factors were treated equally to simplify the approach and not influence results with assumed policy weightings. This differs from the marine spatial planning approach of inclusion of weighting of some factors.

The approach adopted for this study is intended to remove decision-making and instead provides a broad evidence base by testing multiple scenarios that support understanding of how different interactions between other sea activities and marine environments impact relative LCOE and spatial distribution.

This meant that a cell that overlapped with two different soft geospatial factors would be considered twice as constrained as another cell that only had one factor. The list of factors below could be treated as either hard, soft or not considered in any particular scenario to test the impact of these decisions on the model output:

- Anchorage areas.
- Environmental designations.
- Seabird foraging areas (defined by low, medium, or high impact zones).
- Shipping activity (defined by number of transits per year in 600, 400 or 200 transits per year bands).
- Fishing areas (defined by landed value).
- Coastal buffers (between 13km and 40km).

2. Methodology

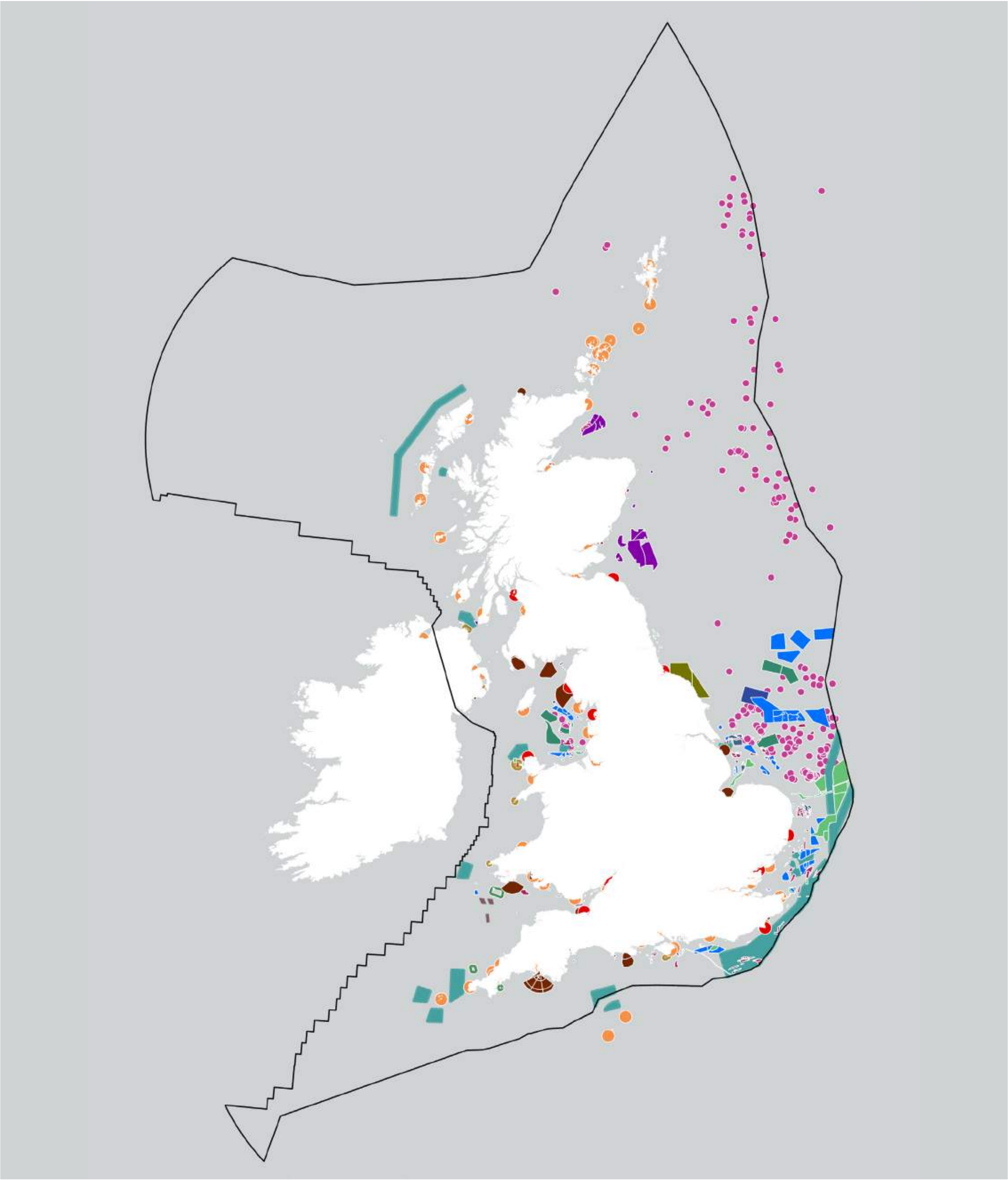


Figure 10.

Map showing the geospatial factors that are treated as hard across all scenarios, which cover 5% of the available UK EEZ waters

Following consultation with stakeholders, this study included the largest spatial extent of the datasets for these key factors:

– 10th percentile bandings of **fishing** landed value (Figure 13).

– Low to high impact areas for **sensitive seabird foraging areas** (Figure 15). The low-density dataset is not included because it covered the entirety of UK waters and would have excluded all cells in the model when treated as hard in Scenarios 8 and 10.

– Number of transits per year of **shipping** activity alongside marine traffic separation schemes (Figure 14).

In addition to these factors, initial analysis highlighted others which, when treated individually as soft or hard, had less than a 2% impact on LCOE when compared with the lowest-cost case. The cumulative effect of including all these lower-impact factors was explored in Scenario 2 of the study and taken as soft in all scenarios following Scenario 2. These factors covered:

– A further 1.5 nautical miles of buffer around the traffic separation schemes (TSS zones themselves are always treated as hard).

– Shipping routes that cover extent of 200 transits per year or less (without buffer).

– Designated sites including Special Protected Areas, Marine Conservation Zones, Marine Protected Areas.

– High-intensity seabird foraging areas.

– Fishing zones for the top 60% of landed value or less.

– Oil and gas platforms with a nine nautical mile buffer around them.

– Radar zones with a 200m buffer.

– Soft military practice areas.

– Medium-intensity recreational sailing areas or below.

2. Methodology

Risk flags were initially considered to differentiate cells that were equally attractive in terms of LCOE and soft geospatial factors but included a factor that would be addressed at a detailed project level. However, this approach was unnecessary because each cell could be distinctly ranked against other locations and deployed consecutively, so instead these were not considered in the analysis.

The final modelling did not consider the following factors which were shown to have less than 1% impact on the LCOE when considered as hard in isolation during early model runs:

– Cables and pipelines.

– Sites of Specific Scientific Interest and Ramsar sites, which are predominantly located inland or in coastal areas.

– Aquaculture lease areas.

– Marine archaeology areas.

– Civil radar interference.

– Helicopter routes to oil and gas platforms.

It is acknowledged that these are important factors that would be considered during the planning and design of individual wind farms, and potentially aspects of strategic deployment planning.

2.3 Scope of model

This study was intended to provide an objective and comprehensive evidence base to support future decision-making. When reviewing the output from the analysis, it is important to take into account the limitations of the modelling.

Data quality

The output of any model is only as good as the input data. Data sources considered in this study, such as MPAs, CCS agreements, and oil and gas decommissioning, are time limited and are likely to change in the timeline captured by the modelling. Some datasets could benefit from further refinement:

Seabird foraging surveys that are recent and high-quality across UK waters are limited. We have taken data from the best available sources to identify higher to lower risk areas for seabird foraging. As the data currently stands, the areas identified from higher to lower risk are large and so are difficult to draw detailed conclusions from. Gaining a better understanding of key seabird activity and areas that require protection from other marine activities requires further surveys of greater coverage, undertaken to a consistent methodology. It should also be noted that the influence of climate change on shifting patterns of predators and prey to 2050 are unknown and will affect the distribution of these areas.

The approach adopted was considered the most practicable given the limitations of existing data, there is a lack of consistent data on the density of seabirds at sea. Notwithstanding the limitations of the seabird foraging layers, they are considered to provide a reasonable and conservative indication of the relative additional risk that offshore wind development would pose in a given area.

However, this does not equate to an indication of whether development within an area might be acceptable or constitute an adverse effect on one or more seabird species which formed part of an SPA population. This would depend on the findings of a detailed site-specific assessment and consideration of cumulative impact.

Fishing datasets differ in their level of detail across Scottish waters and the rest of the UK waters. A combined dataset has been formed to take the best available data.

CCS datasets available were limited and high-level, only identifying large geospatial areas of potential future CO_2 storage – although ongoing studies are currently being undertaken by the North Sea Transition Authority (NSTA), previously the Oil and Gas Authority (OGA). For this study we concluded that the dataset available was too generic to be incorporated into final scenario analysis. More detailed CCS datasets on potential CO_2 storage sites and their associated infrastructure would benefit future studies.

Coastal buffer for visual impact. While marine planning approaches, particularly the recent Marine Scotland's Sectoral Plan for Offshore Wind, consider a complex array of parameters to inform location-specific 'coastal buffers', it was not possible or appropriate within the scope of this study to adopt the same methodology. Instead, we modelled a range of coastal buffers on a UK-wide basis (based on likely buffers to limit visual impact of larger 15MW+ WTGs[10]). Further studies could consider different regions of the UK in greater detail and develop a more refined marine planning approach.

2. Methodology

Figure 11.

Map showing radial connections of cells to onshore substations. Each cell was assumed to connect radially to the nearest onshore substation in one of the 27 ESO charge zones (plus one additional zone created for Northern Ireland).

Moving from a radial to coordinated hub approach

The analysis assumed each offshore wind cluster connected radially directly to the closest onshore substation as illustrated in Figure 11. This approach is a modelling simplification. In reality, export cable routes for radially connected wind farms would be defined on a project-specific basis.

The model did not include any capacity restrictions at the onshore substations. The resulting geospatial distribution of offshore wind clusters from this study could therefore be used to indicate where future network reinforcement might be required in various scenarios.

However, future offshore wind farms will likely connect to offshore coordinated infrastructure, which could encourage clusters to form around certain locations and potentially deliver cost savings at a national scale.

This topic is being developed further in parallel projects by the OTNR, such as the Offshore Coordination Phase 1 report in 2020[5]. Outcomes from this study will inform ongoing and future OTNR work. Further development of this study could include incorporating ongoing studies on network transmission and the potential move to a coordinated grid.

Early modelling of a coordinated offshore hub approach showed the expected clustering of offshore wind farms around them. However, it was outside the scope of this study to undertake an offshore coordinated transmission review, so the final output of this study only includes output from radial connections.

This illustrates the locations that are beneficial for offshore wind when balancing geospatial factors and LCOE. Locations that are common across scenarios show the areas with high potential that should be the focus of further study and possible investment into grid coordination and reinforcement, and supply chain capability. In turn, insight from these studies may influence the location of future deployment.

In addition, we introduced a **density cap** to encourage the geographical spread of clusters. This is partly to represent the limiting factors that would be introduced by onshore grid capacity restrictions, although the density cap cannot fully account for this and further work taking into account the OTNR study, once published, is recommended.

Supply chain

Further, ongoing investment in regional capability to develop offshore wind is needed for the UK to meet its targets for 2030 and beyond. To enable this study to inform where future investment would be best placed, we excluded existing limitations on future offshore wind development from the input parameters.

Hydrogen

An assessment of hydrogen has been carried out as a high-level sensitivity on the baseline modelling. Understanding the role that hydrogen, and, in particular, offshore wind farms ‘dedicated’ to hydrogen production, may have in the future energy mix requires further study as part of a whole-systems assessment, as well as refinement as the costs of offshore electrolysis become clearer.

2. Methodology

2.4 Stakeholder engagement and model refinement

Broad and complex analysis

It was crucial that we sought input from a wide range of industries, public bodies, conservation groups, and other interested parties. They contributed via an online questionnaire, virtual workshops, presentations and direct engagement, and we thank all the organisations involved in shaping this analysis.

Approach to engagement

We held virtual, interactive workshops over two days in April and June 2021, with over 50 attendees. These sessions introduced stakeholders to the project and its objectives, discussing the perceived key LCOE drivers and geospatial factors for offshore wind, as well as gaining feedback on the overall approach proposed.

In addition, 38 stakeholders completed a comprehensive online questionnaire, covering questions relating to the proposed methodology. The responses covered industry views on critical assumptions such as net zero pathways, geospatial factors, physical datasets, cost drivers and learning rates.

To refine the methodology, we held further direct engagement with the OTNR, Natural England, The Wildlife Trusts, the NSTA, ESO, Marine Scotland, NatureScot, OWEC members and the Project Advisory Group (made up of 10 stakeholder groups).

Direction to the model approach

Feedback from these conversations and workshop polling, as well as the questionnaire responses has been fed into the modelling approach and used to determine the scenarios and sensitivities modelled.

Stakeholders agreed with the approach to net zero pathways and with the physical datasets used in the LCOE modelling. They indicated which geospatial factors and cost drivers were most important to them. This informed the areas of focus.

The key themes consistently identified and of most interest to the broad stakeholders were:

- **Environmental designations**
  - Marine SPAs
  - SACs (marine mammal and habitat)
  - MCZ/NCMPA (habitat and mobile feature)
  - Seabirds outside MPA
  - Fish spawning and nursery areas
- **Commercial fishing**
- **Shipping / navigation routes**
- **Coordinated grid**
  - TNUoS charges
  - Distance to grid and the adoption of a coordinated grid approach to offshore wind
  - Hydrogen production
- **Option fees**
- **Cost of capital** – sensitivity in case of no revenue support mechanism

Through the selected model sensitivities and the ten geospatial scenarios, we analysed these topics (except for option fees, which were out of scope), focusing on the themes of interest.

In addition, stakeholders provided direction on the datasets available and the spatial extent of key datasets. As a result, we selected the largest spatial extent of key datasets, such as fishing landed value, sensitive seabird foraging areas, and shipping activity. Stakeholders indicated that the need for greater coexistence presented an opportunity for further analysis, and in general agreed that there should be a whole-system approach to marine spatial planning, which considers the cumulative impact of multiple factors.

3. Key messages

3. Key messages

3.1 Interactions between key geospatial factors that will influence future distribution of offshore wind

The modelling indicates that avoiding interactions with other sea activities and interests will drive offshore wind development to a limited number of areas. This may create risks in system resilience and delivery as well as potentially pushing up the cost of net zero. Whole-system planning and marine spatial planning will enable more informed decision-making and pragmatic balancing of the many different interests.

Of all the factors considered, shipping, fishing, and sensitive seabird foraging areas have the greatest influence on spatial distribution of offshore wind deployment.

This is due to the significant spatial extent of these activities, and because they overlap with preferable locations for offshore wind, based on a low relative LCOE.

Figure 12 shows the spatial extent of known shipping, fishing, and sensitive seabird foraging areas. The only areas that do not feature these geospatial factors are in the central North Sea and at the furthest extents of the EEZ around Scotland and off Cornwall. Co-location opportunities will need to be explored further through marine spatial planning to support co-existence of activities.

There is a large overlap in the spatial distribution of these three dominant geospatial factors, meaning that trying to avoid these cumulatively is not significantly harder than avoiding only one of these factors.

Following stakeholder feedback, the study considered the largest spatial extent of shipping, fishing and sensitive seabird foraging. Using lower thresholds of these datasets, with smaller spatial extent, would open up more space.

Establishing more detailed datasets – especially for areas of seabird foraging – and considering the granular activity levels of each geospatial factor will be key to striking a balance.

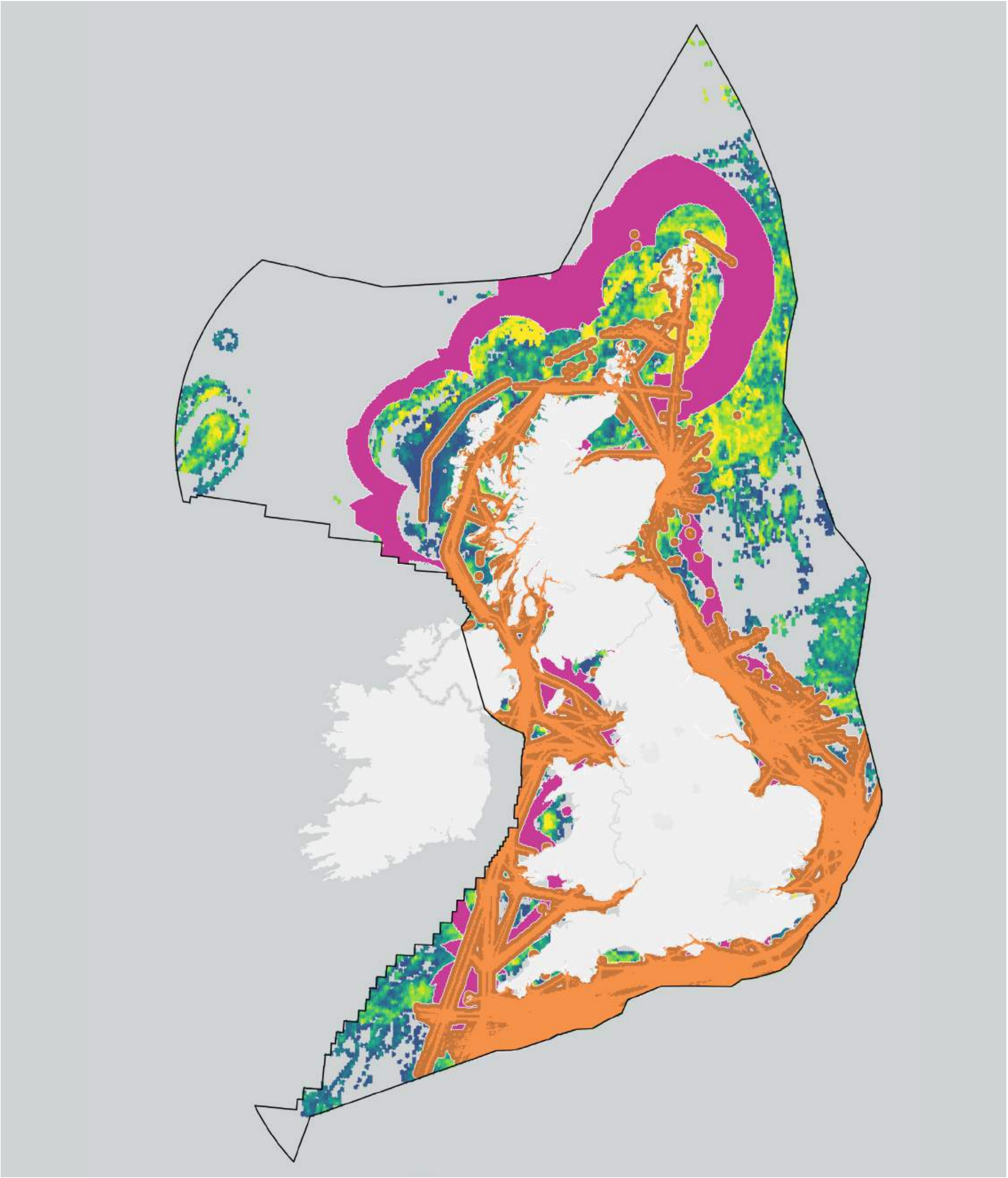


Figure 12.
Map showing the applied dataset extent of the three most influential geospatial factors (fishing, shipping and seabird foraging), which cover a large extent of UK waters.

3. Key messages

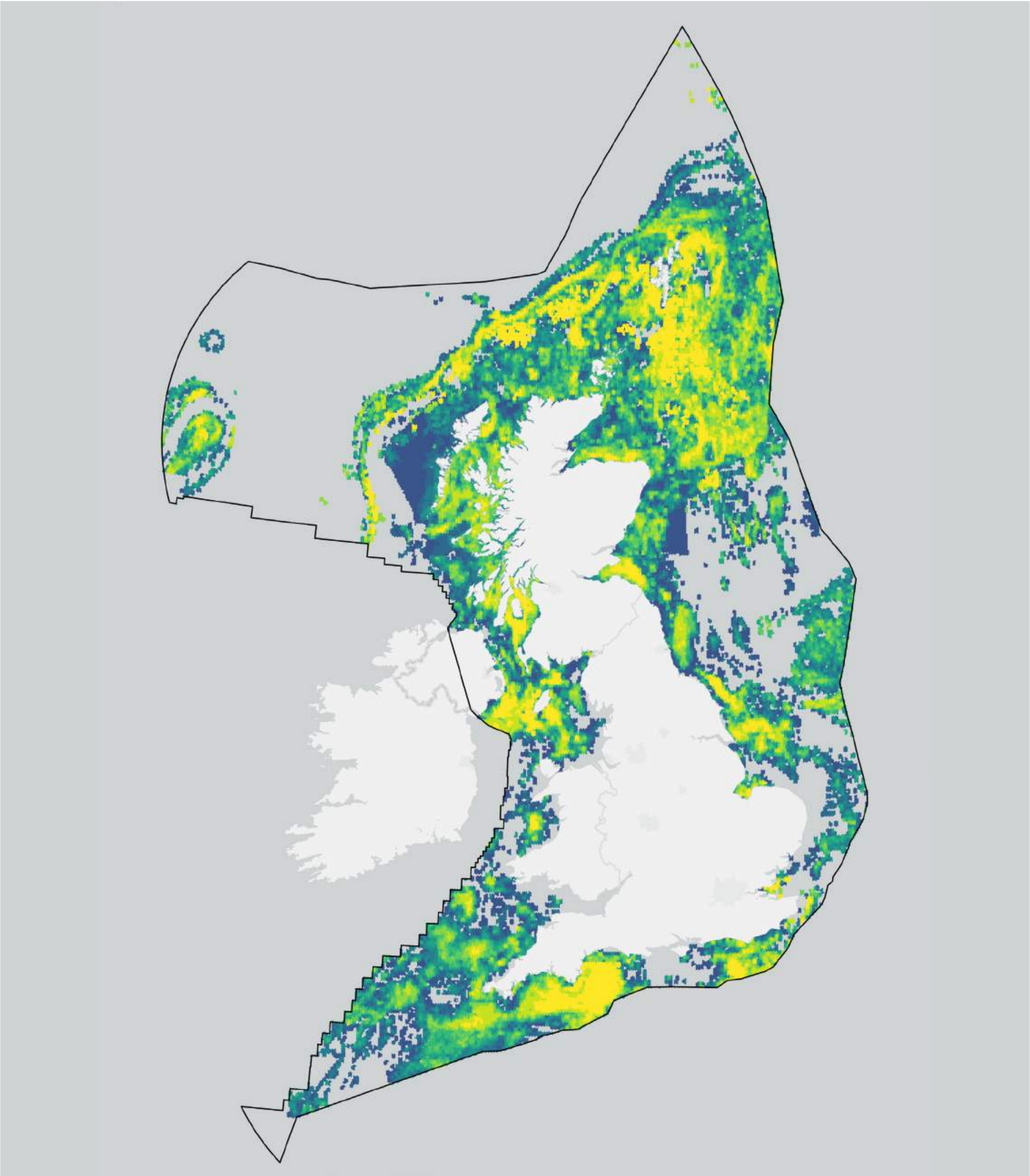


Figure 13.

Map showing the coverage of different percentages of fishing landed value.
The modelling included the highest tier (100%) - all of the landed value decile classes.

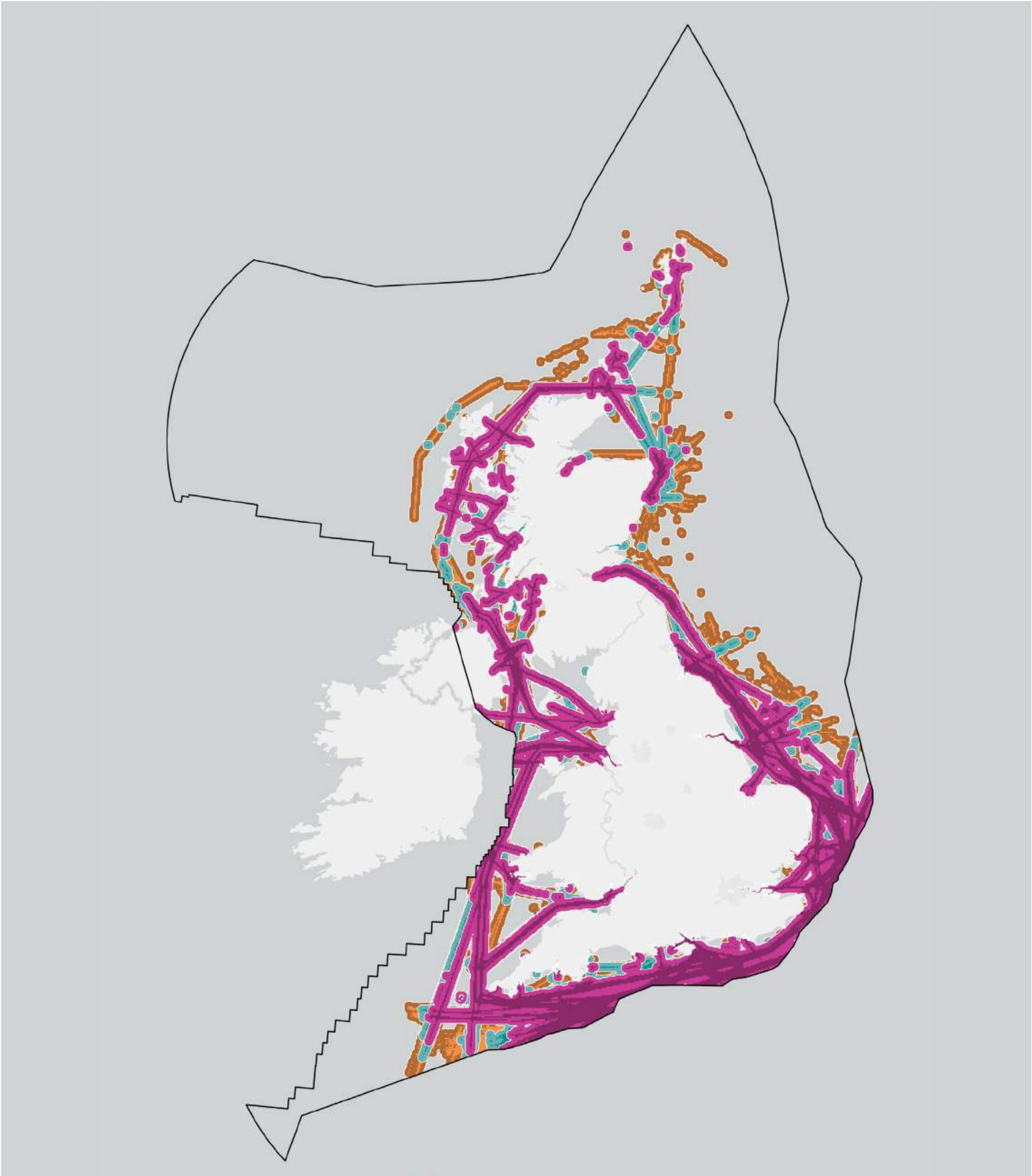


Figure 14.

Map showing the width of shipping channels considering different transit densities and buffers around them. The modelling assumed the most conservative shipping dataset that included >200 transits with a 3.5 nautical mile buffer.

Figure 13 - Legend

Commerical fishing landed value (decile group)

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Figure 14 - Legend

Shipping density

- >600 transits
- >600 transits (3.5nm buffer)
- >400 transits
- >400 transits (3.5nm buffer)
- >200 transits
- >200 transits (3.5nm buffer)

3. Key messages

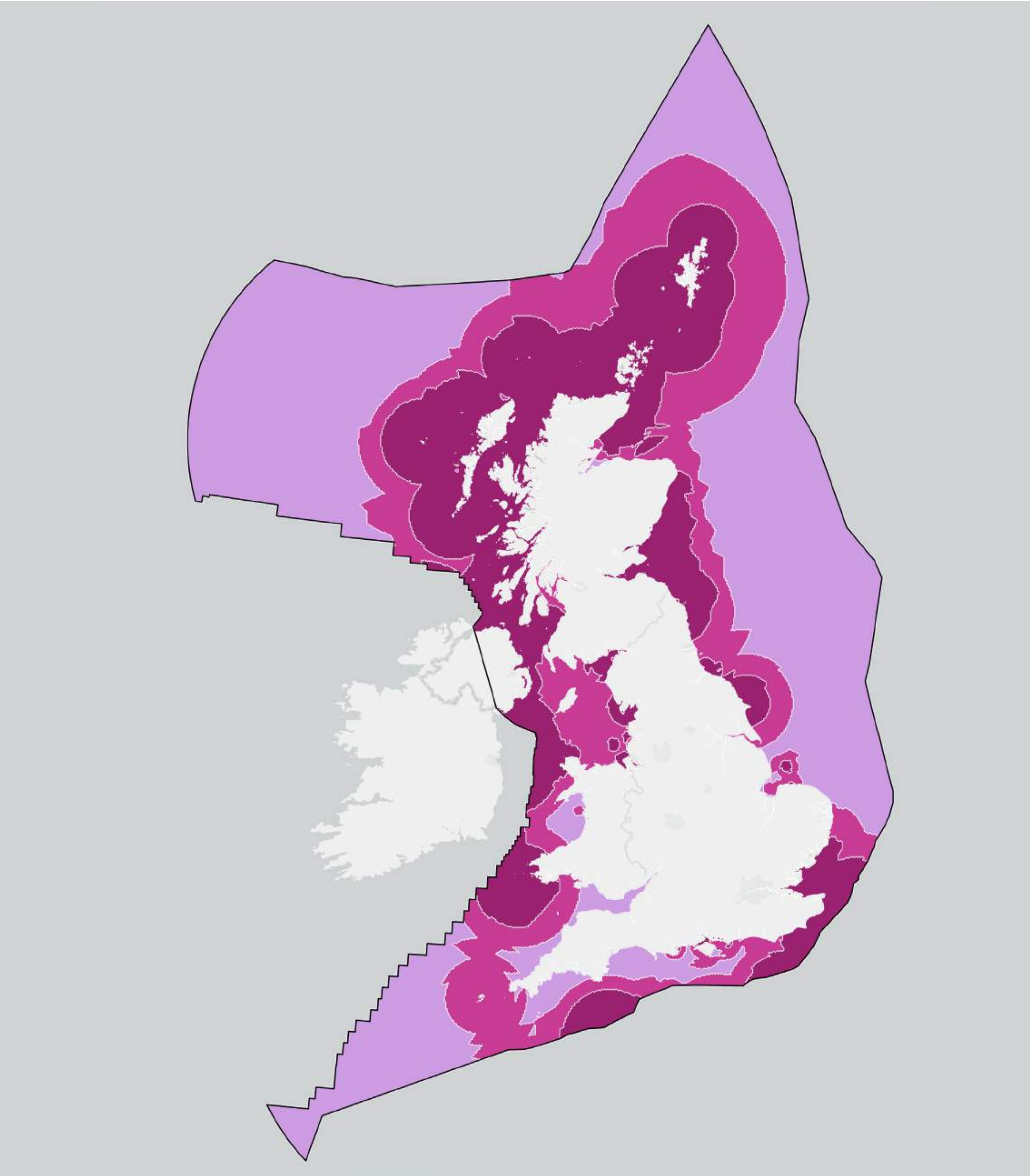


Figure 15.

Map showing the extent of different seabird foraging risk datasets. The modelling took the medium intensity foraging range (rather than the low-density dataset that covered the entirety of UK waters and would have excluded all cells in the model when treated as hard in Scenarios 8 and 10).

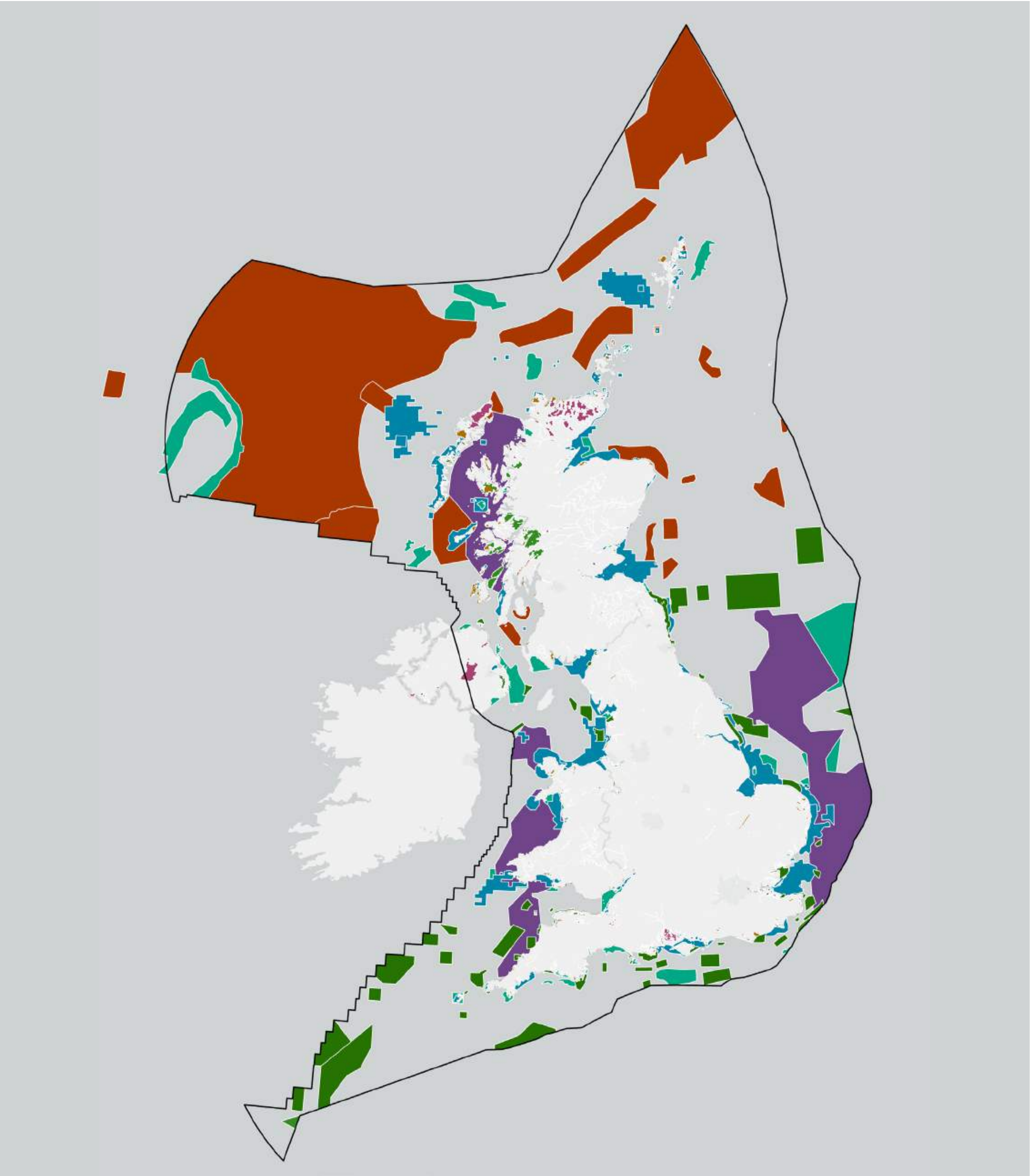


Figure 16.

Map showing location of designated sites included in the modelling.

Figure 15 - Legend

Bird foraging range density

- High density
- Medium density
- Low density

Figure 16 - Legend

- MCZ
- JNCC SPA
- JNCC Marine Mammal SACs
- SNH MPA
- SNH Demo & Research MPA
- JNCC Habitat SACs
- SSSI
- JNCC Ramsar
- Natura 2000 Offshore

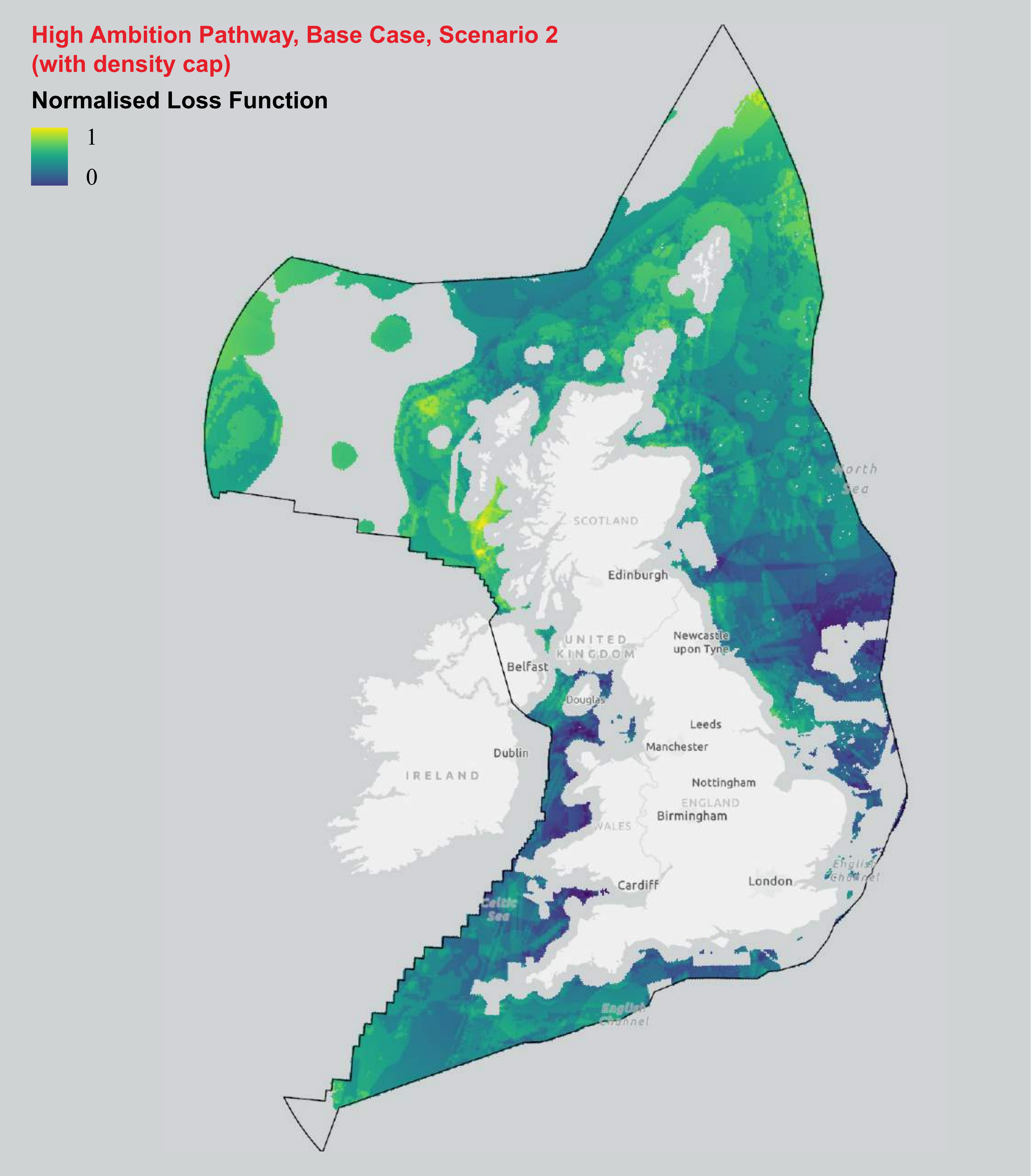
3. Key messages

There are distinct areas around the North-East coast of England that would suit offshore wind deployment across a range of scenarios, considering geospatial factors and LCOE sensitivities.

The research explored different geospatial scenarios – agreed following stakeholder engagement on the key influences, and through discussion with BEIS, The Crown Estate, and Crown Estate Scotland – that demonstrate the influence that marine spatial planning approaches could have on both spatial distribution of offshore wind and relative LCOE. The scenarios considered a multitude of geospatial factors as defined in Section 2.1, which together are likely to significantly impact the overall future deployment.

The outputs are discussed against Scenario 1, which although not realistic, as it prioritises LCOE and does not consider any geospatial factors apart from those that are always treated as hard, provides a lower bound scenario.

In Figure 17 and Figure 18, offshore wind development is allowed to occur in, but still looks to avoid, areas of fishing, shipping, sensitive seabird foraging areas, and environmental designations. Scenario 5 presents a more constrained view taking higher tiers of the fishing, shipping and seabird foraging considerations compared to Scenario 2 as set out in Table 1. Projects cluster around the relatively low-cost areas of the central North Sea and Irish Sea based on the balance of the geospatial factors and lowest LCOE.



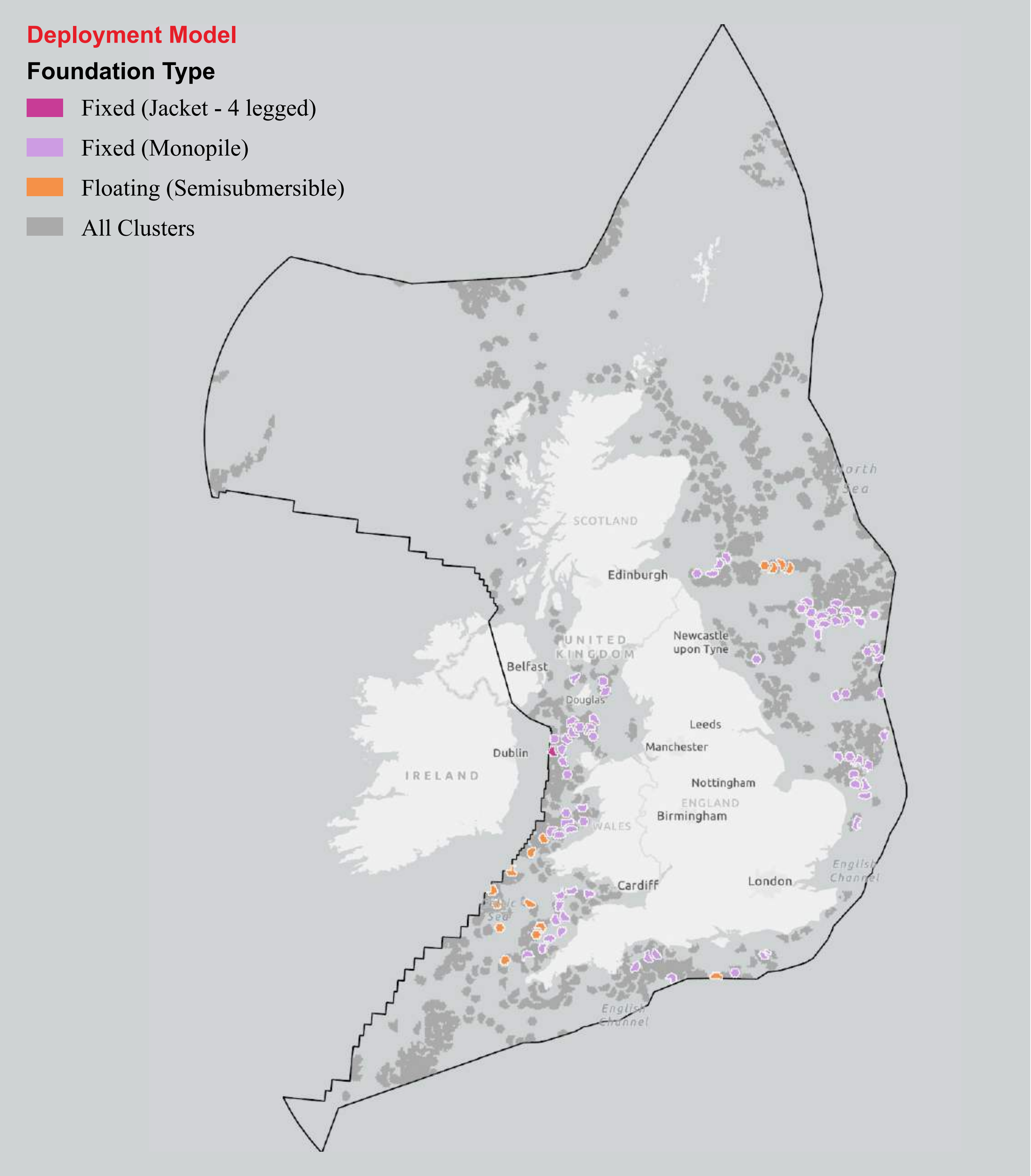
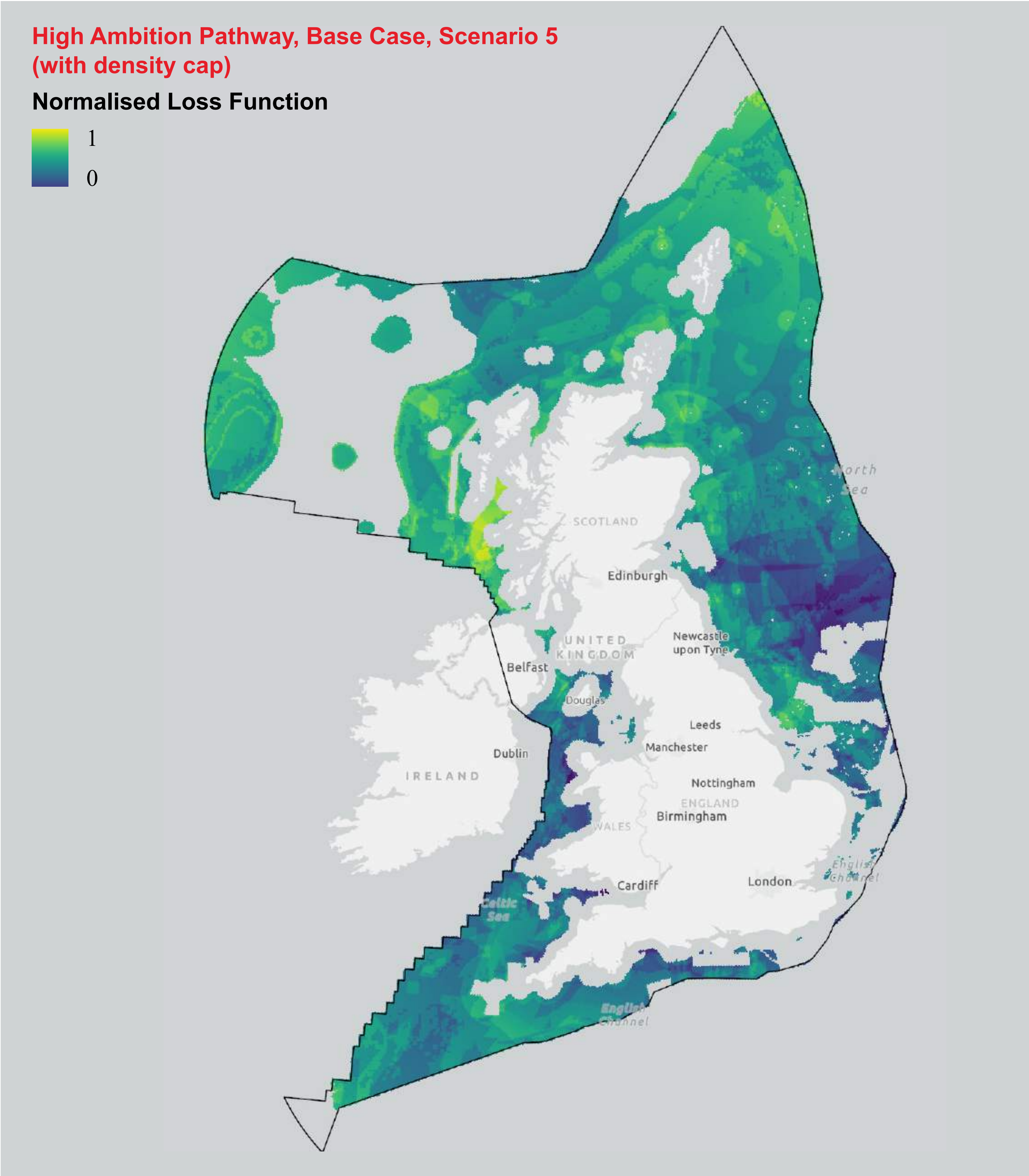


Figure 17.

Left: Heat map showing the value of the normalised loss function, ranging from low (deep blue) to high (yellow). Right: Map showing the output of the deployment model, with individual wind farm locations colour-coded according to foundation type. Offshore wind deployment interacts to a certain extent with other geospatial factors, but tries to avoid these areas based on the balance with increasing LCOE (High Ambition pathway, Base Case, Scenario 2)

3. Key messages



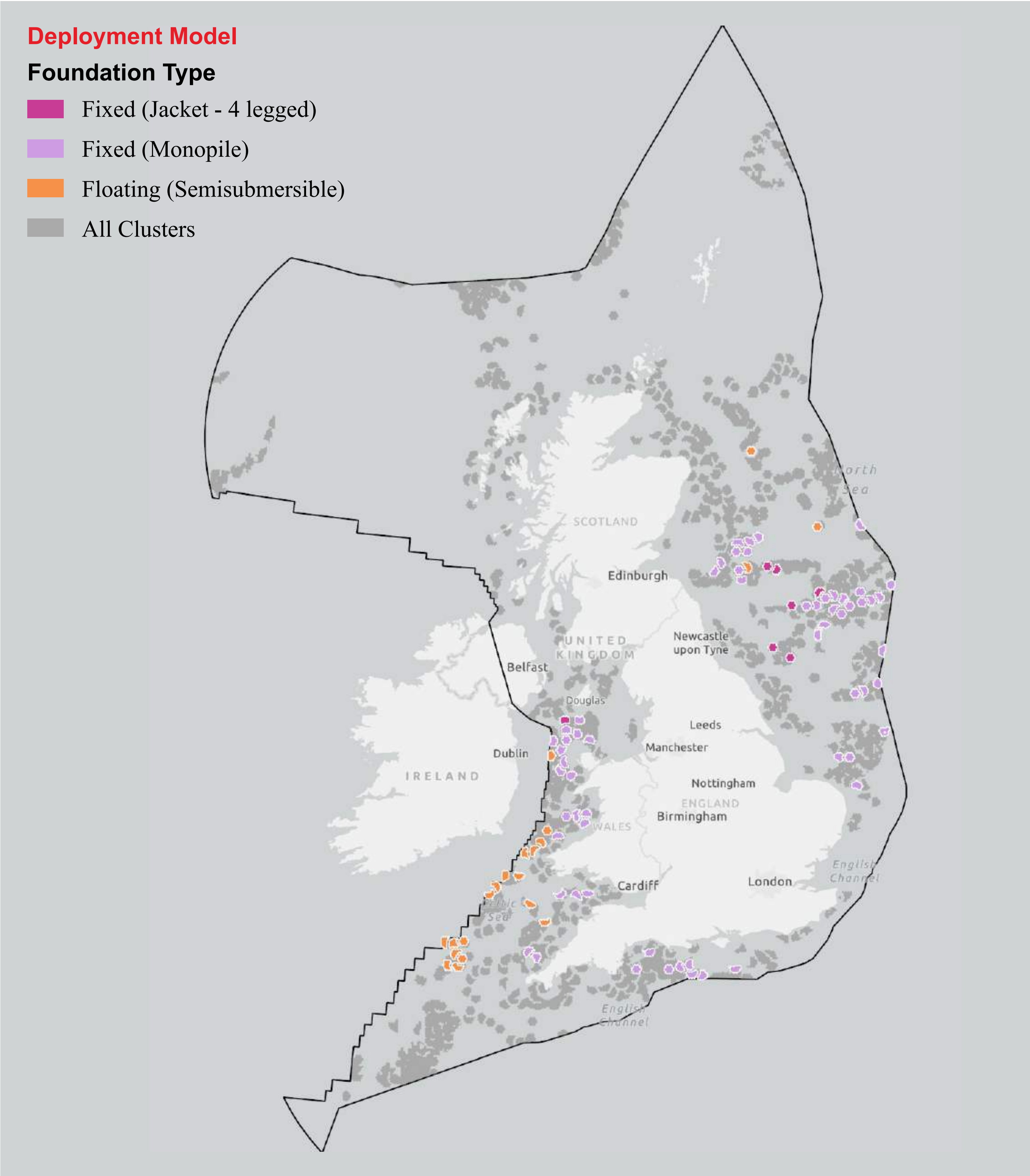


Figure 18.

Heat map showing the value of the normalised loss function, ranging from low (deep blue) to high (yellow). Right: Map showing the output of the deployment model, with individual wind farm locations colour-coded according to foundation type. Offshore wind deployment interacts to a certain extent with other geospatial factors, but tries to avoid these areas based on the balance with increasing LCOE (High Ambition pathway, Base Case, Scenario 5)

3. Key messages

Figure 19 demonstrates the impact of limiting interaction between offshore wind and other key geospatial factors as summarised in Table 2.

The data associated with the bird foraging range density is subject to a high level of uncertainty and has a limited ability to convey the overall sensitivity of these areas and related to species to offshore wind farm development. Research continues to inform the individual sensitivity of birds and their key areas of habitat use, and further study would better inform decision making to protect sensitive seabird species and support a balance with offshore wind deployment. The results from this study have been generated to investigate potential sensitivities at a strategic level and do not represent potential policy positions or planning guidelines.

Key

⊗ Hard

✓ Soft

⬇ Soft (applied to lower tiers of the geospatial factor)

	Scenario 2	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 10
Co-existence allowed with fishing	⬇	✓	⊗	✓	✓	⊗
Co-existence allowed with shipping	⬇	✓	✓	⊗	✓	⊗
Co-existence allowed with seabird foraging and environmental designations	⬇	✓	✓	✓	⊗	⊗
Relative portfolio LCOE increase compared with lower bound Scenario 1	9%	14%	20%	20%	24%	34%

Table 2.
Impact on relative LCOE of avoiding co-existence with the three most influential geospatial factors.

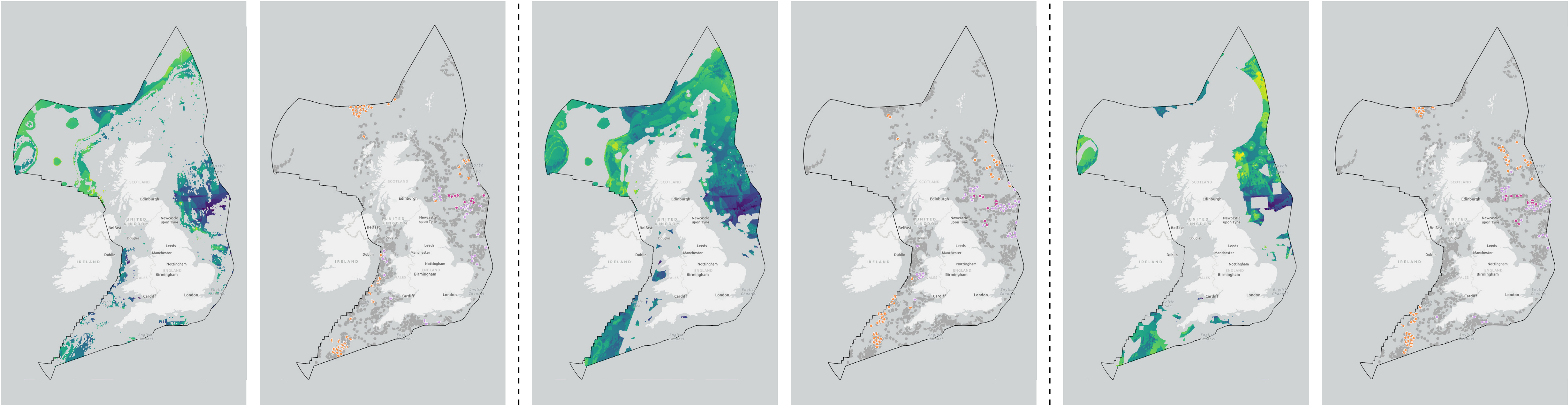


Figure 19.
Heatmaps and deployment model output showing the effect of limiting offshore wind coexistence with the most influential geospatial considerations: fishing (left), shipping (centre), and seabird foraging and environmental designations (right) (High Ambition pathway, Base Case, Scenarios 6, 7, and 8 from left to right)

When these geospatial factors are taken cumulatively and offshore wind deployment is prevented in all locations where they feature, as shown in Figure 20, there is very little remaining footprint in the UK EEZ and so limited flexibility for offshore wind deployment elsewhere in UK waters.

This results in the model focusing deployment in the relatively unconstrained and low-cost area in the central North Sea and pushes deployment far from shore around the perimeter of the EEZ.

This scenario (Scenario 10) does not present a realistic view of the future of offshore wind deployment but demonstrates the impact that preventing deployment in any of these locations could have.

This is an interactive document, please use the buttons to see larger images within the figure.

3. Key messages

Despite Figure 20 showing a very high constrained view across all modelling runs, it was consistently able to deploy the full 140GW target of the High Ambition pathway.

Including floating wind in the portfolio makes it possible to deploy offshore wind further from shore where there are fewer other factors present, assuming the necessary grid infrastructure can be built to facilitate this.

While building in such locations may be more expensive up to the late 2030s, beyond this a tipping point may be reached on price competitiveness with fixed foundations closer to shore. This supports a greater contribution from floating wind, which could be achieved faster as evidenced by the strong presence of floating wind in the recent ScotWind leasing round offers.

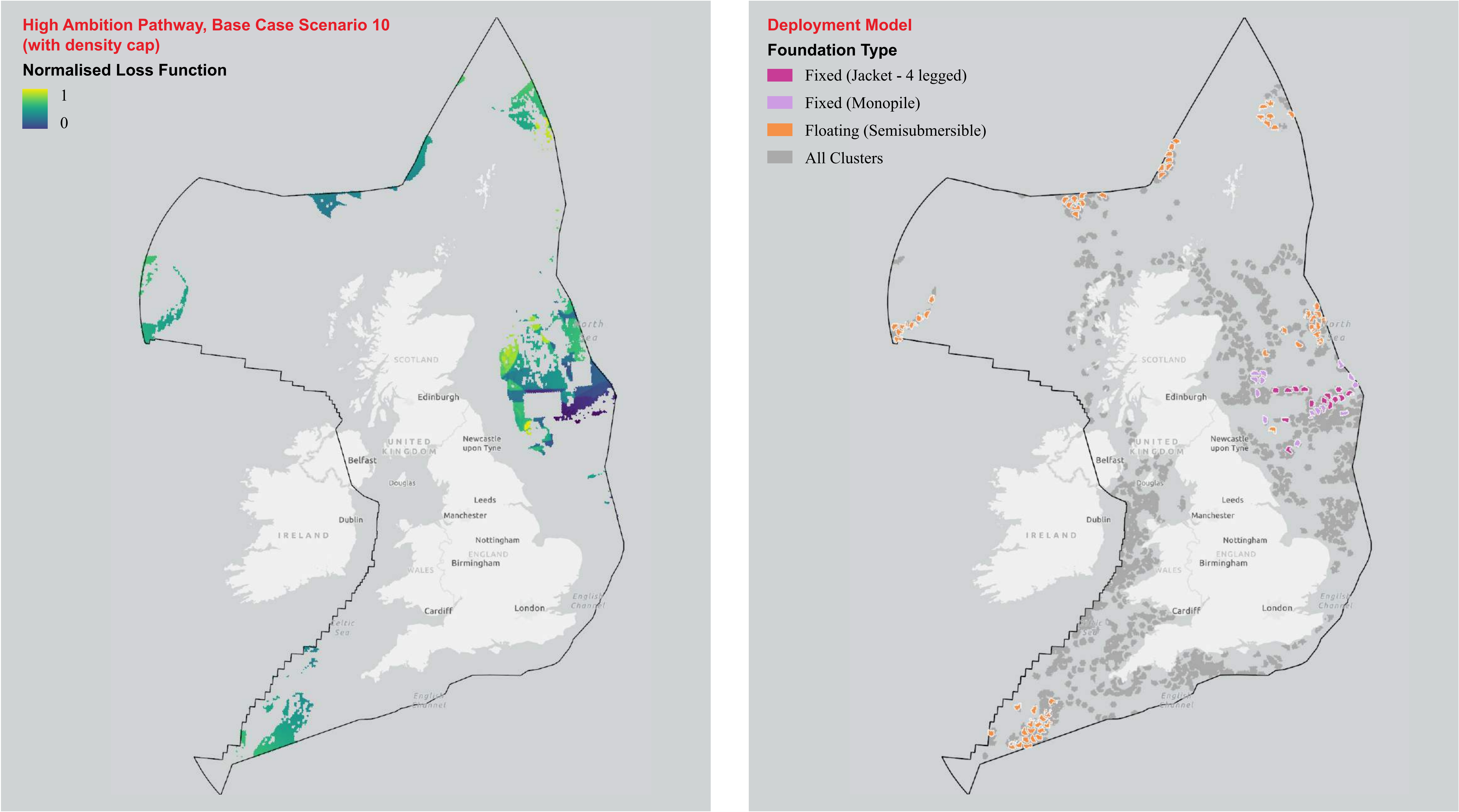


Figure 20.

Heatmap and deployment model output showing the effect of limiting offshore wind interaction with key geospatial factors of fishing, shipping, seabird foraging and environmental designations, which leads to much reduced areas of seabed being available for deployment (High Ambition pathway, Base Case, Scenario 10).

3. Key messages

3.2 Regional distribution and influence of wider system factors

Several other factors such as onshore grid capacity and supply chain capabilities, not within the scope of this study, will influence offshore wind distribution around the UK and should be included in future whole-energy-system reviews.

Figure 21 represents the diversity of spatial distribution across all modelled scenarios. Significant proportions of UK waters will need to be developed to deliver the UK's Net Zero Strategy[4], representing approximately 10% of the area identified in the macro analysis opposite.

- Active NSTA Platforms
- Wind Site Agreements
- Wind Leasing Round 4 Preferred Projects
- Nuclear Power Stations (10km buffer)
- IMO Traffic Sep. Schemes
- Navigational Dredging
- CAA Airports (10km buffer)
- Minerals Aggregates Site Agreements (1km buffer)
- Tidal Stream Site Agreements (5km buffer)
- Natural Gas Storage Site Agreements
- Carbon Capture and Storage Site Agreements
- Open Dredge Disposal Sites
- Crown Estate Scotland Energy Sites
- Coastal firing ranges
- Floating Offshore Wind Test and Demo Sites

Count of scenarios per cell

- 1 - 8
- 9 - 23
- 24 - 44
- 45 - 73
- 74 - 117

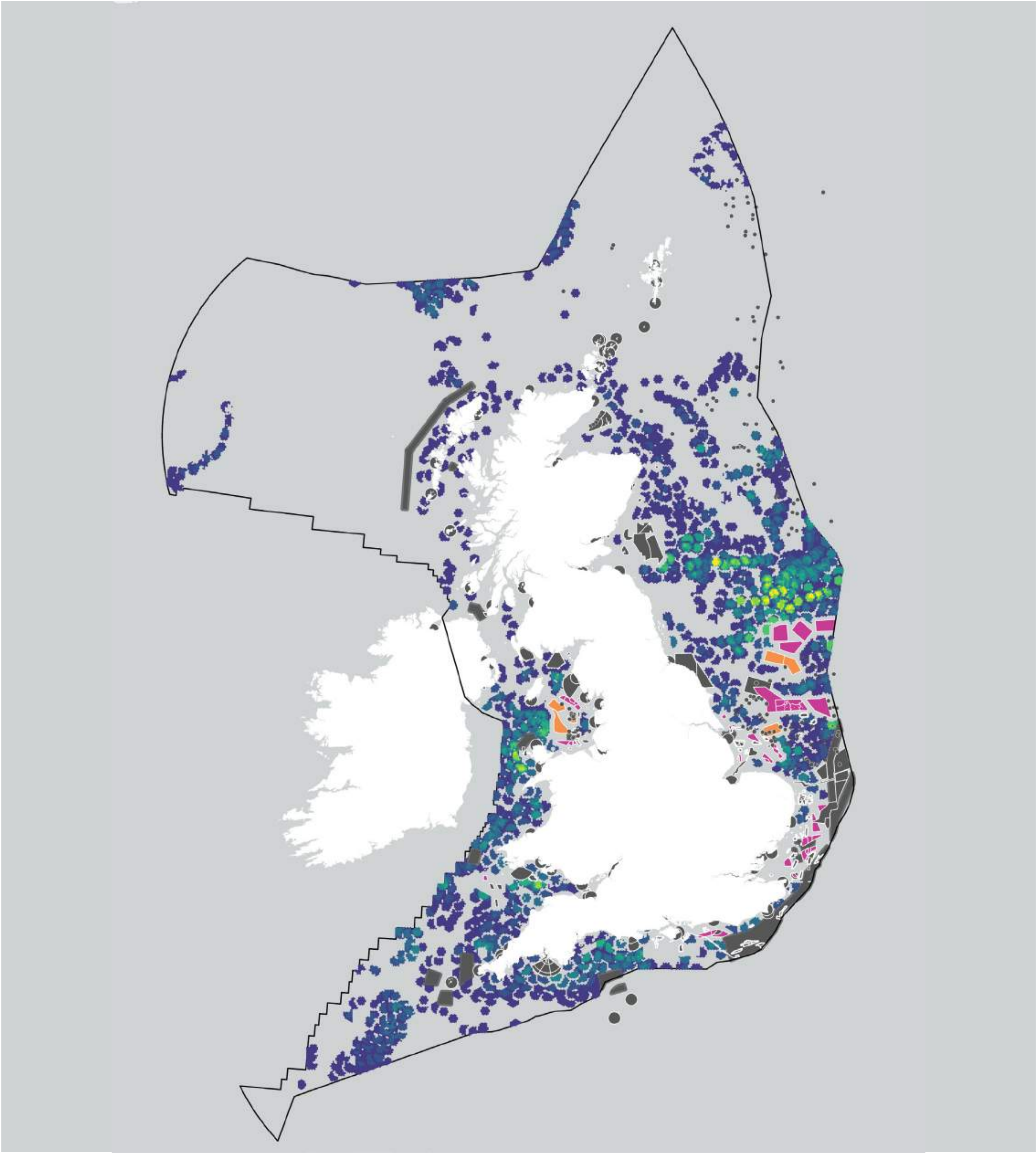


Figure 21.

Heat map showing potential deployments in all modelled outcomes. Geospatial factors treated as hard in all scenarios are outlined in grey for reference, and offshore wind leasing sites in orange and pink (excluding ScotWind leasing sites). Cell colour represents the frequency with which that cell is deployed across all scenarios, ranging from dark blue (least frequent) to yellow (most frequent).

The central North Sea region features frequently in the modelling output as it combines a relatively low LCOE with lesser presence of other geospatial factors, and it is suitable for either fixed or floating foundations. Figure 24 shows areas of relatively lower (blue) or higher (yellow) LCOE across the UK EEZ boundary, with the central North Sea zone featuring relatively low LCOE.

There is likely to be significant risk associated with consolidated development and many factors, not considered within this study, that will influence offshore wind distribution around the UK.

Factors including onshore grid capacity, location of large energy demand centres, potential future coordinated network 'hubs' or other coordinated grid solutions, and supply chain capability will influence the spatial distribution. Other factors will influence how much offshore wind is deployed in a particular area, including wake effects across adjacent wind farms or the cumulative environmental impact of clusters of offshore wind deployment.

3. Key messages

Current TNUoS charging | Removing influence of TNUoS | Wide extrapolation of TNUoS forecasting

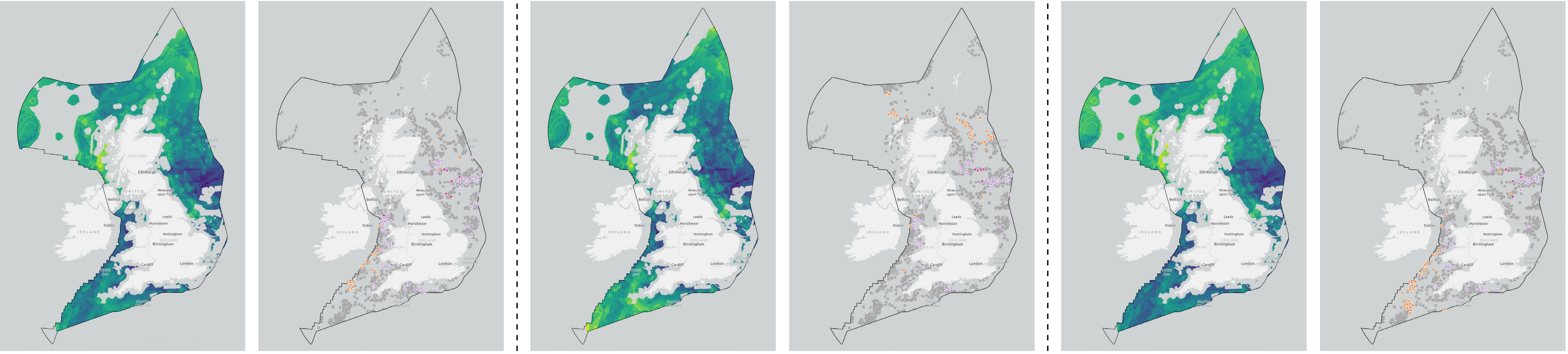


Figure 22.
Heatmaps and deployment model output showing the effect of current TNUoS (left), removing the locational cost component of TNUoS (centre) and extrapolating the 5-year TNUoS forecast (right) (High Ambition pathway, Scenario 5).

Current TNUoS charging | Removing influence of TNUoS | Wide extrapolation of TNUoS forecasting

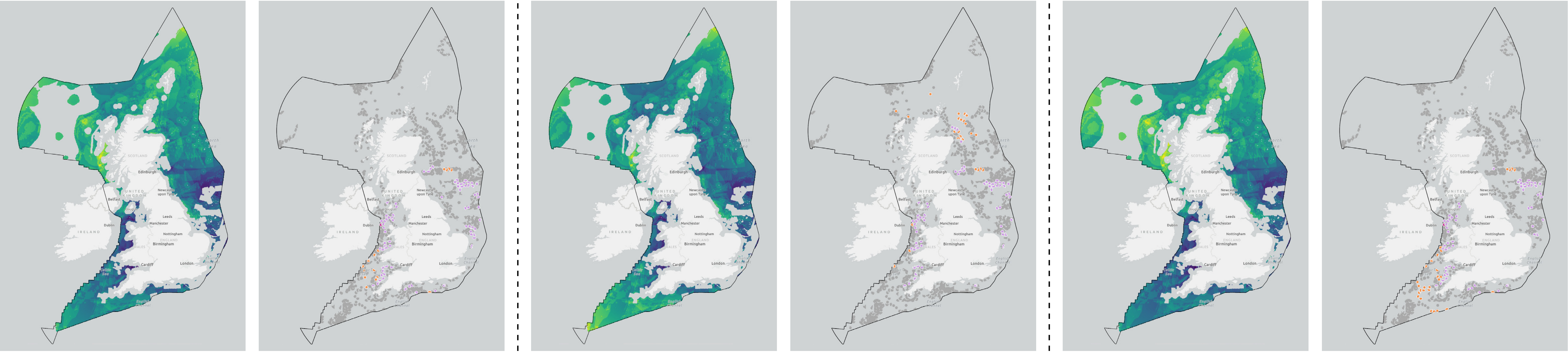


Figure 23.
Heatmaps and deployment model output showing the effect of current TNUoS (left), removing the locational cost component of TNUoS (centre) and extrapolating the 5-year TNUoS forecast (right) (High Ambition pathway, Scenario 2).

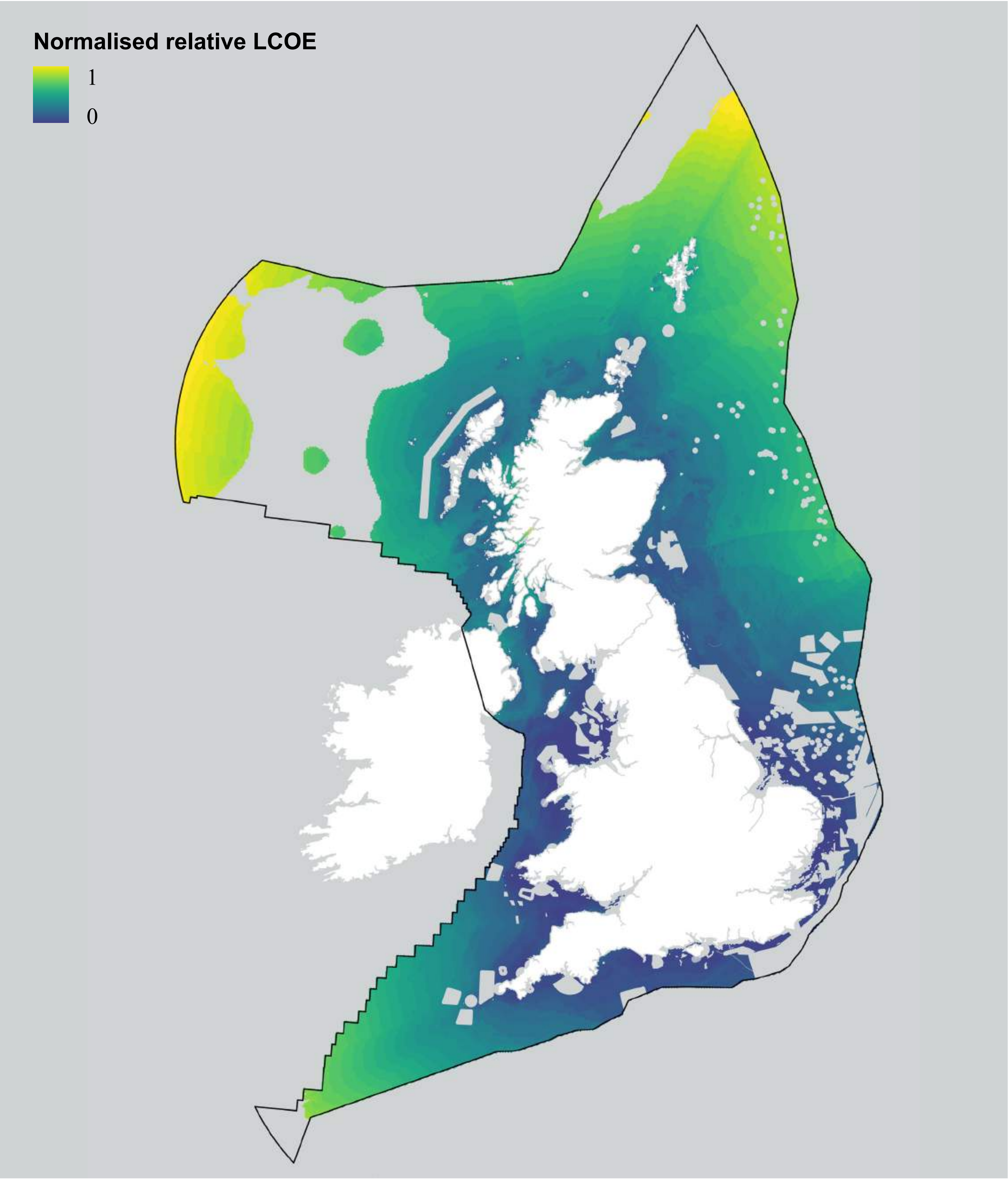


Figure 24.
Heatmap showing normalised LCOE for Base Case, with the lowest cost cells in blue and the highest cost in yellow.

3. Key messages

Impact of network charging and the transmission grid

The modelling highlights the influence of network charging on the geospatial distribution and portfolio cost of offshore wind. Sensitivities on network charging were run to understand the potential impact of either removing the existing differences in network charging or continuing the current trajectory as illustrated in Figure 22 and Figure 23.

> Without the locational price signal of TNUoS there is wider geographical distribution across most scenarios, although the variation is less obvious in scenarios featuring other dominant geospatial factors.

In particular, the approach to transmission charging could greatly influence the geographical spread of offshore wind. If current trends in TNUoS charges continue, costs will be lower towards the south of the UK.

Based on ESO's grid charge zones[7], BSUoS is constant across regions, and it was assumed to stay constant with time. Including or removing it varies the overall portfolio LCOE by 15% but has no relative influence or effect on the geospatial distribution of offshore wind deployment. Note that BSUoS charges are expected to be removed in 2023 to align the GB electricity market more closely with EU member states[6].

TNUoS, on the other hand, introduces a large cost differential across the UK – as much as £38/kW separate the highest-charge regions in Northern Scotland from certain zones in the South-West of England that have negative charging[8]. This resulted in less deployment in Scottish waters. This effect was apparent across the three pathways and regardless of the treatment of geospatial factors.

We explored the effects of removing the locational component of charges by setting TNUoS charges to zero across all grid charge zones. There is an opportunity to encourage further development in Scottish waters by re-assessing how TNUoS is implemented across the UK, although the network upgrade costs of large-scale development in Scotland would still need to be funded by transmission users and accounted for at a whole-system level.

On the other hand, if the current regional trends published by ESO in their five-year annual forecast[8] are assumed to continue diverging over time, deployment in the model is further driven to the South-West of England and Wales. There would be other system-level considerations – such as grid capacity, supply chain and port capability (covered in other sections of this report) – that would limit the concentration of deployment in any one area. But this sensitivity highlights the potential impact on a broader distribution of offshore wind development related to this upper bound modelling of TNUoS charges.

In both Figure 22 and Figure 23, offshore wind development is allowed to occur in, but still looks to avoid, areas of fishing, shipping, sensitive seabird foraging areas, and environmental designations. Scenario 5 presents a more constrained view taking higher tiers of the fishing, shipping and seabird foraging considerations compared to Scenario 2 as set out in Table 1.

3. Key messages

3.3 The role of floating wind

Floating wind will play a role in delivering net zero by 2050, but there is uncertainty about the extent of its role in the overall offshore wind portfolio. Over 14GW of floating wind option agreements offered in the recent ScotWind Leasing Round demonstrate the industry’s confidence in these emerging technologies and may accelerate the learning rates assumed in the modelling base case.

In the study, the contribution of floating wind to the overall portfolio varied widely depending on the overall deployment target of the pathway, system-level sensitivities, and treatment of geospatial factors.

The contribution of floating wind to the total portfolio averaged 31% across all model runs, ranging from 0% of the wind farms deployed in the model up to a maximum of 70%.

This upper bound occurred when offshore wind was prevented from co-existing with the three most influential geospatial factors – fishing, shipping and sensitive seabird foraging areas – that take up large areas of near-shore waters and push offshore wind to deeper sites.

Figure 25 demonstrates that while there is a general positive correlation between increasing floating wind and increasing portfolio LCOE, it is also possible to achieve similar levels of LCOE across the portfolio with varying contributions from floating wind, depending on which areas of seabed are available and how much deployment is targeted.

Increasing the level of floating wind does not necessarily cause a direct increase in portfolio LCOE because other dominant factors, such as distance from shore, influence the LCOE of a windfarm.

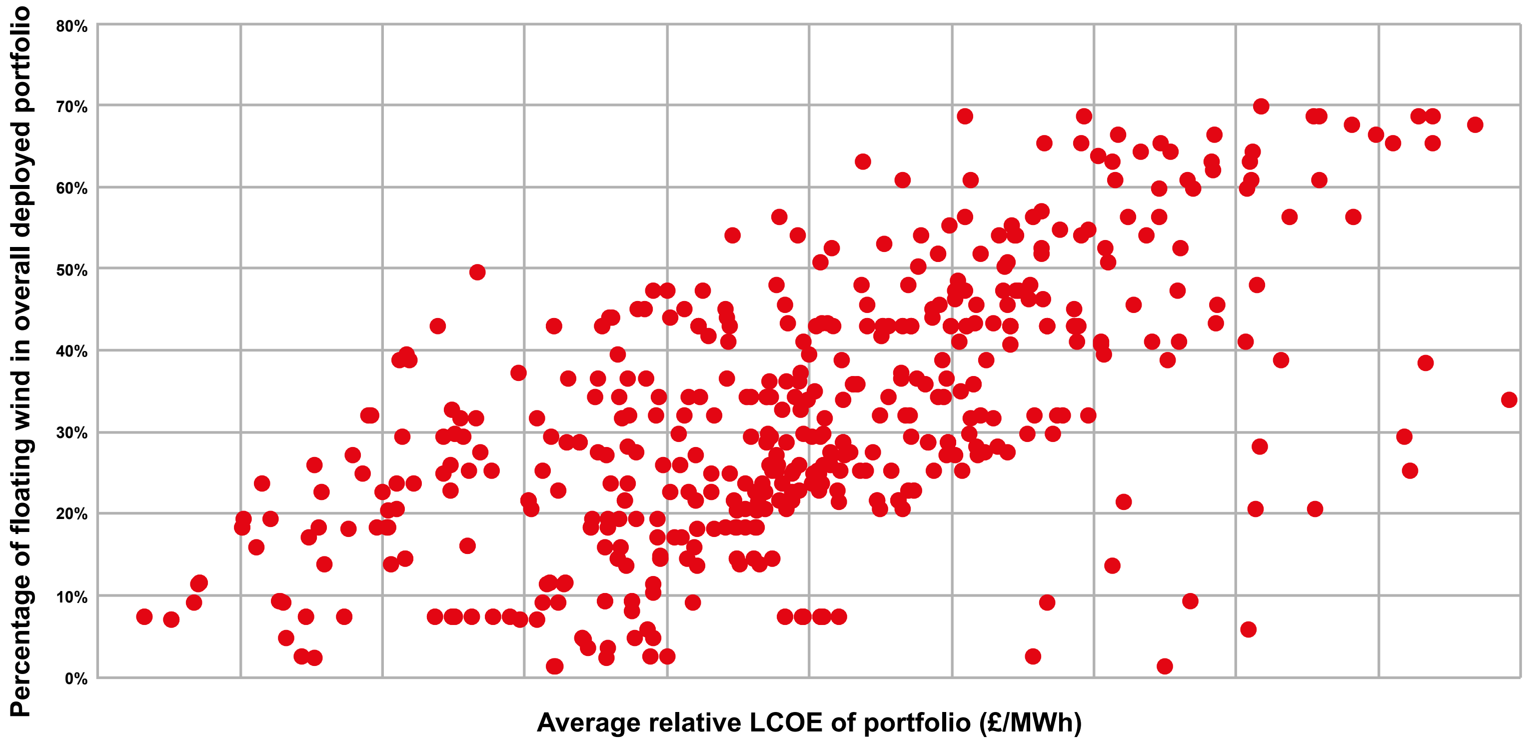


Figure 25.

Scatter plot showing the relationship between the percentage of floating wind foundations and average relative LCOE for the deployed portfolio across all model runs

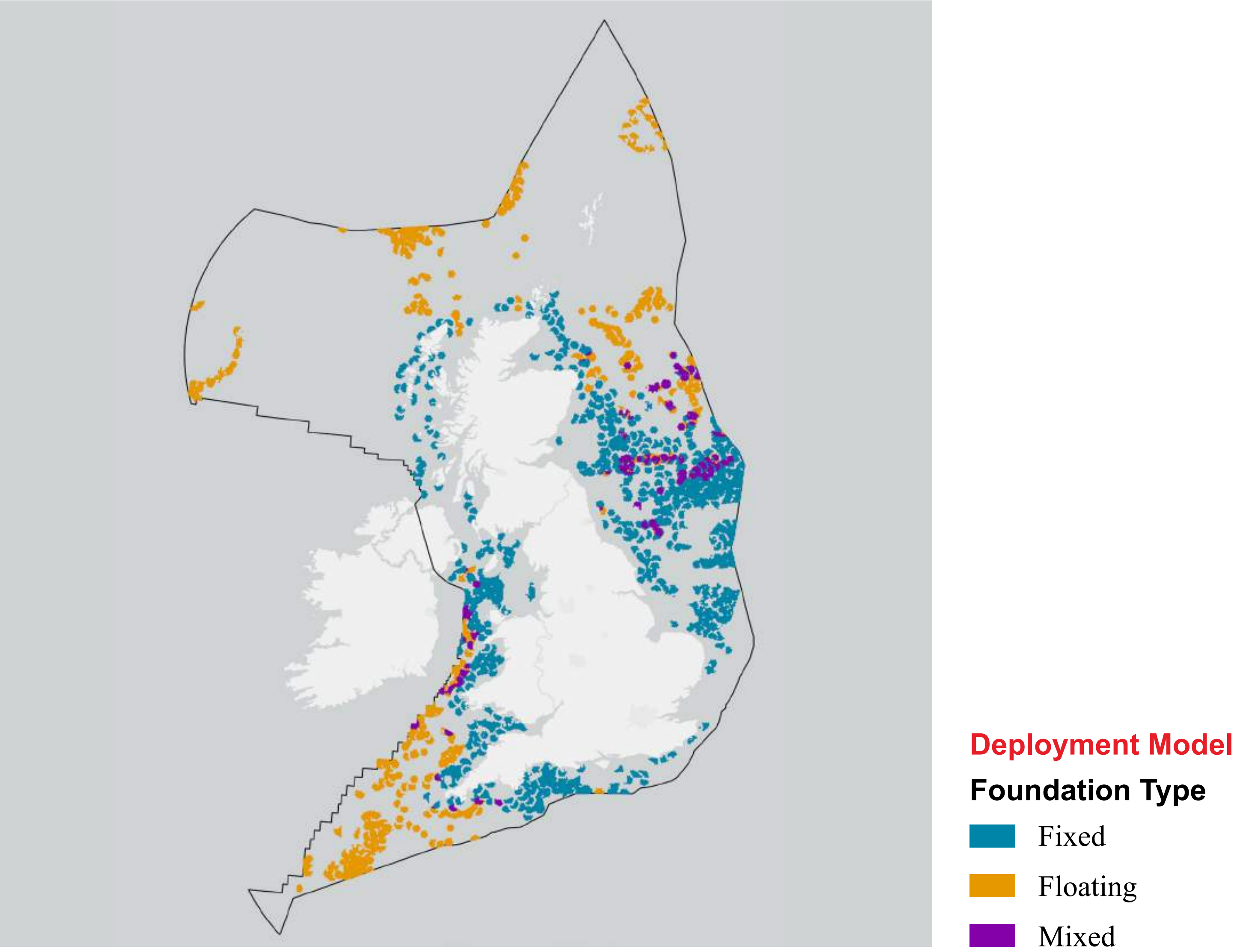
The timeframe within which floating technologies could become a cost-competitive and viable alternative to traditional fixed foundations will depend on how quickly cost reductions can be achieved. Floating foundations will be more dominant if the industry follows the accelerated learning seen in fixed foundations over the last two decades.

The modelling considers price parity with fixed foundations to be a possibility, and therefore feature more dominantly, from the late 2030s onwards - or sooner if higher learning rates are achieved.

The wide range of scenarios run in the modelling highlight different areas where floating wind could be favoured in Figure 26. Aside from regions far from shore or in deeper waters that are beyond the predicted limits of fixed foundations, floating wind also features in areas that combine favourable site conditions, leading to a relatively low LCOE with reduced overlap with geospatial factors, such as in the central North Sea and in the Celtic Sea. In such zones, the modelling considers price parity with fixed foundations to be a possibility, and therefore feature more dominantly, from the late 2030s onwards.

3. Key messages

The choice of fixed or floating foundations in these locations will likely be driven by the preferred maintenance strategy and the installation, operational, and revenue implications of towing a floating foundation to shore for major maintenance versus maintaining a fixed foundation in a coordinated offshore campaign. Assessing the feasibility of coexistence with activities such as fishing, particularly regarding cabling impact, could also influence this choice. The tipping point is strongly linked to availability, vessel charter rates, and distance from shore.



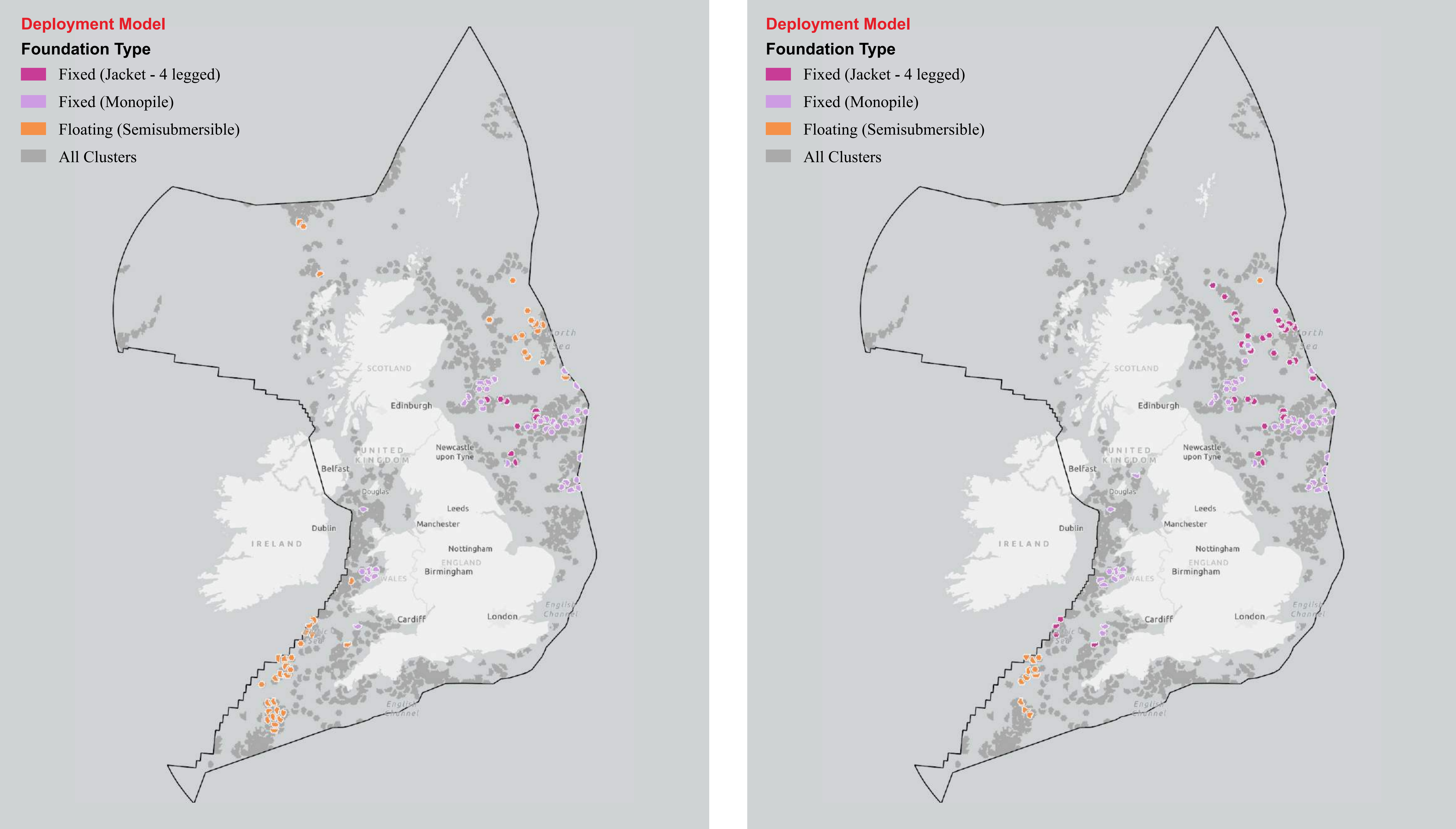


Figure 26.

Deployment model output showing the selected lowest cost foundation (fixed, floating or both) depending on the location, across all model runs.

Figure 27.

Deployment model output showing effect of lowering the learning rates assumed for floating wind for (left: Base Case, right: Floating Learning Rates sensitivity) (High Ambition pathway, Scenario 7).

3. Key messages

Learning rates sensitivity

The Base Case assumed that floating wind technology will follow the same accelerated learning rates experienced by fixed foundations during the first decades of the industry. Reducing the floating learning rates to match those assumed for fixed foundations beyond 2034 is a weaker driver than other factors on the overall spatial distribution of offshore wind, which remains largely unchanged compared with the Base Case.

Compared with the Base Case, reducing the learning rates applied to floating components significantly reduces the amount of floating offshore wind deployed across the portfolio. In five of the scenarios, there is 1% or less floating, and the maximum percentage of floating wind halves from 69% to 54% in Scenario 10.

Figure 26 shows some locations in deep water, far from shore, that are only suitable for floating foundations, as well as other areas where both types of foundations could be deployed. These locations may form part of the overall mix whether or not cost parity is reached, dependent on marine spatial planning decisions and the overall deployment target.

The overall net zero pathway is likely to influence the occurrence of floating wind. The Base Case, High Ambition pathway with a 140GW target saw a step change in the contribution of floating wind across scenarios as shown in Figure 28. On the other hand, when considering lower learning rates for floating in the other two pathways, the required deployment can be met fully with fixed foundations.

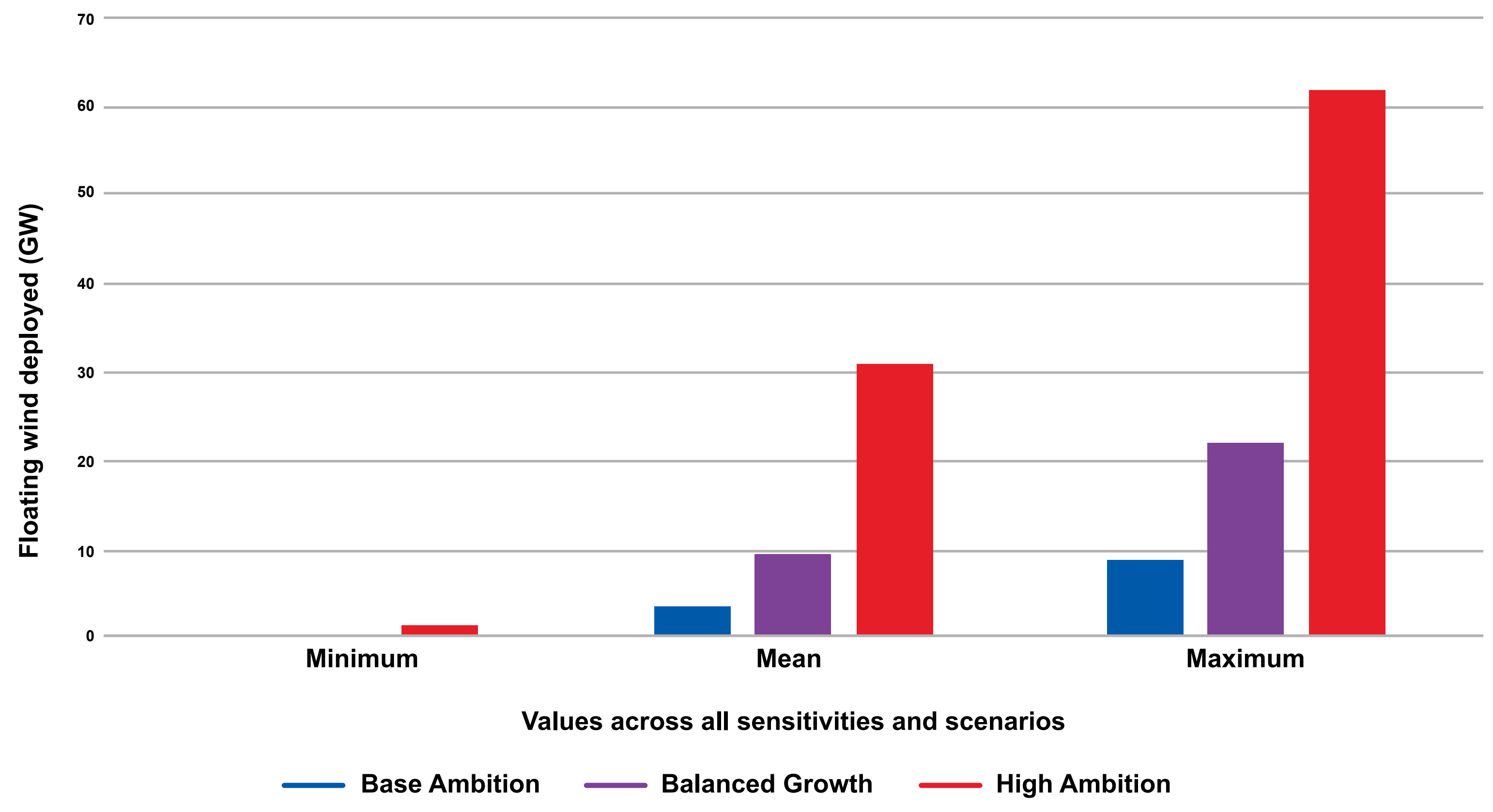


Figure 28.

Graph showing the capacity of floating wind deployed for the three pathways in the scenarios with the minimum, mean and maximum deployment. Minimum floating deployment occurs in the scenario where all offshore wind deployment is close to shore (Scenario 1). Maximum deployment of 60GW occurs in the High Ambition pathway and scenarios where offshore wind is pushed far from shore by other geospatial considerations (Scenario 10).

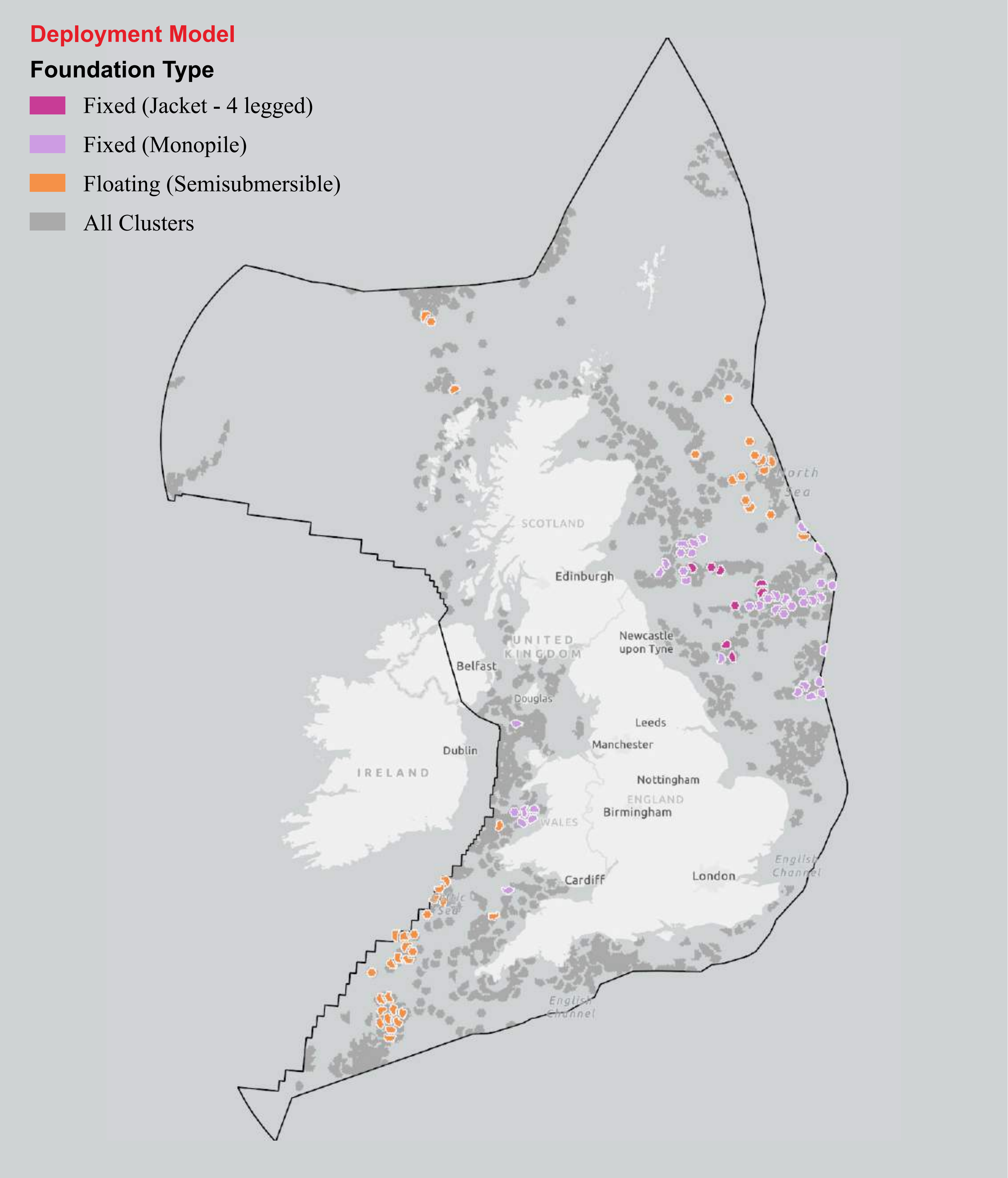
3. Key messages

3.4 Hydrogen as part of the energy mix

Including hydrogen in the portfolio has a minimal impact on the overall portfolio LCOE. Although the assumed onshore hydrogen hubs draw deployment towards them, this clustering effect is less pronounced because the influence of other geospatial factors is more dominant on the spatial distribution of offshore wind deployment.

With green hydrogen predicted to be part of the energy mix required to reach net zero by 2050[1], the research explored – in the High Ambition pathway – the impact on cost and spatial distribution of including offshore wind sites dedicated exclusively to producing green hydrogen. Figure 29 shows hydrogen-dedicated sites in areas that could favour both fixed and floating foundations.

We considered the costs associated with both onshore and offshore electrolysis. Generating hydrogen offshore and piping it to shore is potentially more economically attractive than onshore electrolysis due to capital savings and reduced electrical losses.



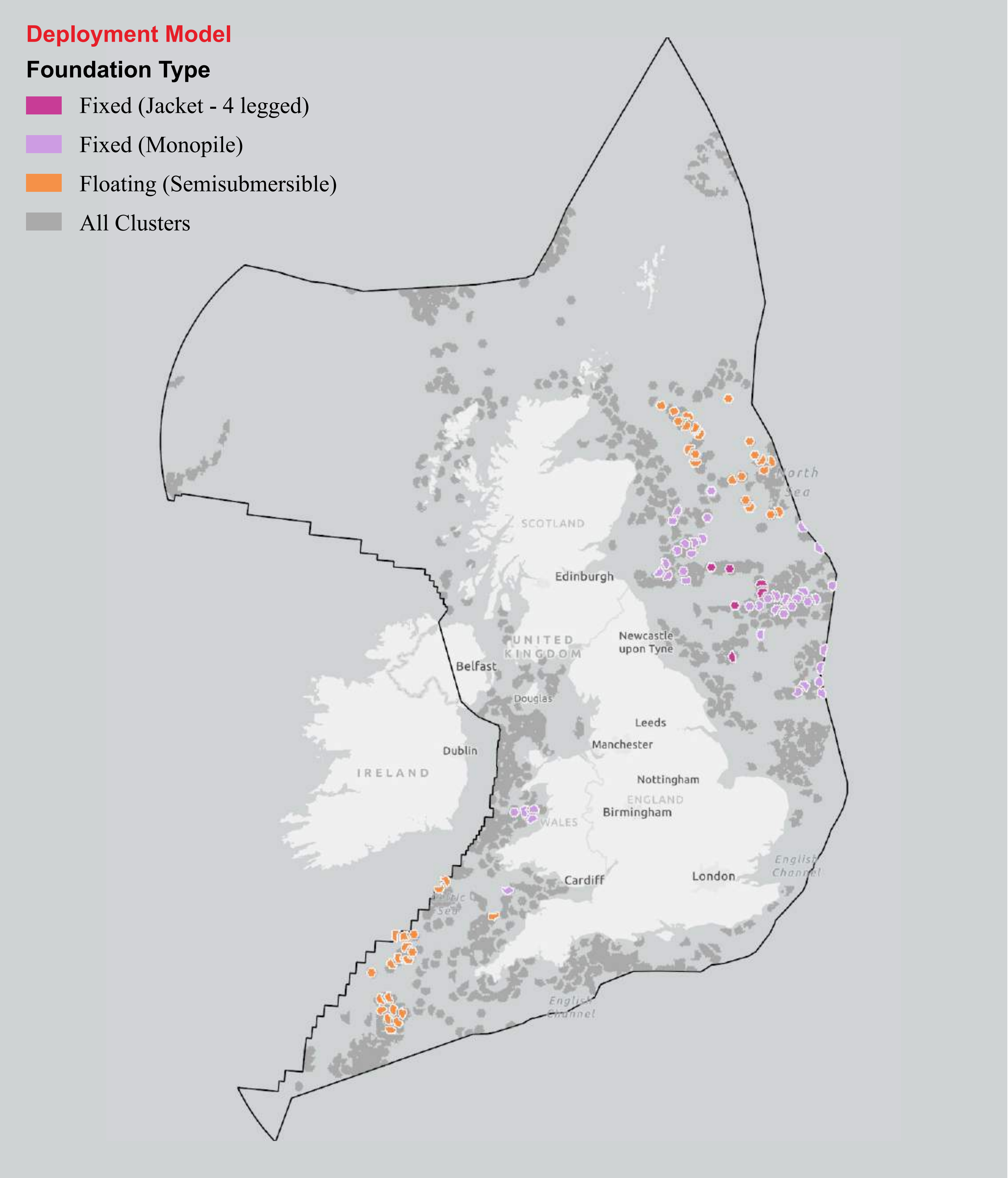


Figure 29.

Deployment model output showing effect of dedicating 40GW of offshore wind to producing hydrogen and transporting to the onshore hubs in Figure 9.
Base Case (left) and Hydrogen Sensitivity (right) (High Ambition pathway, Scenario 7).

3. Key messages

We explored the impact of dedicating 40GW out of the total 140GW of deployment to producing hydrogen for the High Ambition pathway. In general, the geospatial distribution of clusters remains largely unchanged compared with the Base Case.

The impact on the portfolio LCOE of including hydrogen in the energy mix is not significant across the different scenarios compared with the Base Case.

This minimal influence on relative LCOE includes the assumption that the 140GW offshore wind deployed in the High Ambition pathway is absorbed into the UK electricity grid without accounting for the cost of upgrades to enable this. Assigning these (as yet unknown) costs to the overall portfolio cost of delivering 140GW of offshore wind could change the picture and present a stronger case for production of hydrogen to help balance the whole system and the subsequent cost of delivery.

Decisions on where and whether offshore wind is dedicated to green hydrogen are likely to be driven largely by market mechanisms and the extent to which hydrogen is used as a storage vector to support a much greater degree of intermittent renewables on the UK electricity grid.

The balance of complex interactions between seabed uses and the protection of marine environments in policy and marine spatial planning will still govern offshore wind location (whether for electricity or hydrogen production).

There is significant uncertainty around the cost of electrolysers and associated infrastructure for hydrogen production and further work to refine this could result in different outcomes. Nevertheless, the balances between different geospatial factors remain the largest driver of both the spatial distribution and cost of offshore wind deployment, be it for direct electricity production or as part of green hydrogen production.

Cost of capital sensitivity

Contract for Difference (CfD) mechanisms have been in place in the UK since the first CfD allocation round (AR1) in 2015. We explored the impact of removing them on the weighted average cost of capital, and therefore on deployment.

The impact of removing CfD mechanisms on the average LCOE of the portfolio was an increase of less than 1% across all scenarios, compared with the Base Case.

Although the geospatial distribution of clusters remains virtually unchanged when comparing both sensitivities, the percentage of floating wind reduced by an average of 6%. This reflects a delay to achieving cost parity between floating and fixed foundations, as the former would be more affected by an increase in the cost of financing new projects.

3. Key messages

3.5 A wide range of outcomes

This research study has started to build a detailed evidence base, using a digital approach to support analysis of multiple scenarios. This has moved forward the ability of the industry and decision-makers to assess and test the complex array of factors affecting future offshore wind deployment.

This work does not attempt to present a recommended pathway for the UK's future offshore wind portfolio. It provides evidence to support future decision-making and needs to be considered alongside factors outside the scope of this study.

In addition to considering geospatial scenarios, we assessed seven 'system' sensitivities that influence LCOE directly and result in up to a 15% difference from the Base Case LCOE.

The more dominant influences on both LCOE and spatial distribution of offshore wind deployment are the geospatial interactions between offshore wind and other seabed activities and marine environments.

The results show that, for the majority of the sensitivities and scenarios considered, changing the net zero pathway does not have as large an impact on the average LCOE of the portfolio compared with the effect of the sensitivities and scenarios themselves.

Figure 30 shows the range of relative LCOE across the 380 scenarios modelled across different system sensitivities. In addition to a Base Case LCOE, the system sensitivities are:

1. Removal of TNUoS charges from the individual generator level (noting there would be system-level costs that are then unaccounted for in the modelling).
2. Extrapolation of the current TNUoS five-year forecast.
3. Removal of BSUoS.
4. Adjusted weighted average cost of capital assuming the CfD support mechanism is no longer available.
5. Lower floating wind learning rate than assumed in the Base Case.
6. Requirement for 40GW of hydrogen-dedicated offshore wind deployment in the High Ambition pathway only.

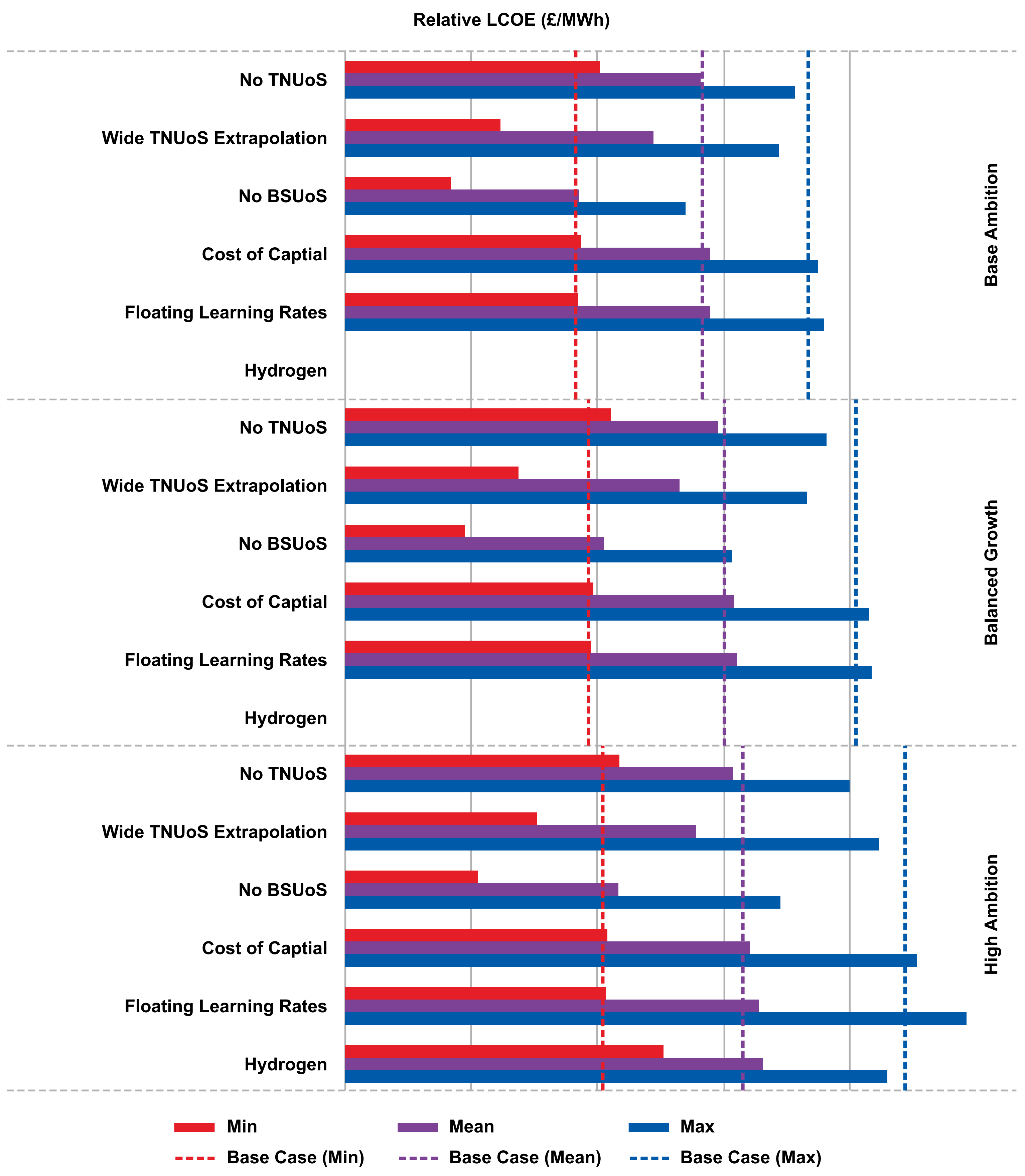


Figure 30.

Plots showing the range of normalised relative LCOE for each sensitivity (with Base Case LCOE as dashed lines for reference), across the full range of modelled scenarios for the three Net Zero pathways.

4. Conclusions

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4. Conclusions

The study has highlighted:

The need for whole-system planning and integrated marine spatial planning

The study has further demonstrated the complexity of marine spatial planning and the future policy and planning decisions that will need to be made in support of net zero. The proposed next steps outlined below and broader industry recommendations in Section 5 provide the potential first steps of a roadmap towards achieving integrated models and planning.

That policy and marine spatial planning decisions will influence the cost of and ability to deploy more offshore wind

Across the geospatial scenarios, system sensitivities and pathways modelled, the output from this study shows the importance of achieving a portfolio that balances the complex interactions between location and portfolio cost of offshore wind, different activities in our seas and protection of the marine environment.

The highest-cost scenario portfolios see deployment in more remote offshore sites, with an emphasis on avoiding other key geospatial considerations.

To achieve significant growth in offshore wind at an acceptable cost, policy decisions must consider other activities in our seas, alongside protecting the marine environment. Decisions about areas defined for shipping, fishing and seabird foraging are likely to be the most influential in determining what a UK offshore wind portfolio will look like in 2050.

Industry support and collaboration could achieve faster floating wind learning rates

If faster floating wind learning rates can be achieved than assumed in the modelling this could provide broader, cost-competitive spatial options sooner. However, it should be noted that technological aspects alone are unlikely to provide a full answer to balancing the multiple complexities and there will still be a need for policy and marine spatial planning decisions that balance these interactions.

Decisions about the UK's transmission network will influence the deployment, and cost, of offshore wind and the UK's net zero energy portfolio

Choices about how, where and when coordinated offshore networks are located could reduce LCOE in locations close to coordinated infrastructure. Understanding the influence of a coordinated approach will need to be iterative, reflecting the way that deployment locations inform transmission design and transmission design informs deployment cost and location.

Early work carried out during this study highlighted the effect a coordinated 'hub' system could have on locational dispersion of offshore wind, with sites closer to any potential future offshore 'hubs' benefiting from lower LCOE with resultant clustering around hub locations.

The locational influence of TNUoS has been explored across a range of sensitivities – from continuing the trend of the current ESO's-year forecast to a sensitivity removing TNUoS. This has demonstrated the influence of this system component on LCOE and on the potential location of a future offshore wind portfolio.

Financial support mechanisms create an environment that encourages investment

The research shows how investor confidence can result in lower LCOE through cheaper financing – by assessment of a higher sensitivity of Weighted Average Cost of Capital. Although this is less influential on a whole-portfolio LCOE to 2050 and does not influence geospatial spread of offshore wind deployment, annual CfD auctions bring greater investor confidence and support a strong pipeline of offshore wind.

Lessons learnt:

Modelling approach

This study used a sophisticated analysis model that takes a data-driven approach to illustrate the interactions between system and technology uncertainties, costs, and geospatial factors, within the bounding model parameters, and across multiple scenarios and sensitivities.

Through the analysis carried out, a broad evidence base has been established that can be used by policymakers, offshore wind developers and industry stakeholders to explore:

- The **complex interactions** between offshore wind, different activities in our seas and protection of the marine environment
- The **influence on relative LCOE** of different future decisions
- The **role of floating** wind.

4. Conclusions

The model deliberately takes a spatially pure approach, driven by coverage of all geospatial factors within a cell. This removes any bias in the modelling, so as not to influence results with assumed policy weightings. This differs from the marine spatial planning approach of including weighting of some factors. The output gives insights into the influence and balance of factors without these weightings. The output therefore does not consider wider aspects of policy decisions, socio-economic benefits or environmental benefits that are considered within marine spatial planning.

The study has further demonstrated the complexity of marine spatial planning and the future policy and planning decisions that will need to be made in support of net zero.

Other complex factors

The model scope did not include assessment of certain other complex factors, many of which are subject to other ongoing studies.

Next steps could include refining the approach to incorporate findings from other ongoing studies when available, and further functionality to assess key parameters that were outside the scope of this study, such as: onshore grid capacity constraints; unknown environmental impact of a large concentration of wind farms in a particular seabed area; installation and operational considerations; wake effects across multiple wind farm clusters; resilience and spread of supply regionally; CCS deployment; and regional supply chain capability.

Next steps

The following next steps are recommended to further add to the growing evidence base in support of future policy and marine spatial planning:

- Using this evidence base to inform approaches in Defra’s Marine Spatial Prioritisation programme, and support general discussion with devolved marine planning authorities, aiding the next steps taken towards whole-system planning and integrated marine spatial planning, potential prioritisation of activities and integrated marine spatial planning.
- Continuing to develop the evidence base through:
  - Assessment of a range of scenarios incorporating weightings to reflect more closely the approaches taken in marine spatial planning.
  - Integration and assessment of broader system factors, including work by others as part of the OTNR, through integration of onshore capacity constraints at substations where appropriate and modelling of potential coordinated transmission infrastructure.
  - Research and assessment of environmental impact of a large concentration of wind farms in a particular seabed area and incorporation of findings into updated modelling to limit the maximum clustering of offshore wind deployment based on research findings.
- Assessment and refinement of installation and operational considerations for wind farms further from shore, to improve certainty around delivery of floating offshore wind in the furthest from shore locations.
- Assessment of wake effects across multiple wind farm clusters to also inform potential plausible maximum size of wind farm clusters in a given area.
- Incorporation of supply chain considerations building on various ongoing studies and supply chain investments around the UK.
- Establishing more detailed datasets and evidence base for activities such as sensitive seabird foraging areas as summarised in Section 2.3 and Section 5.
- Further study into the different features of environmental designations and how these are impacted by offshore wind deployment (including differences between impact of fixed and floating foundations).
- Assessing and discussing in more detail the balance of different levels of activity of seabed considerations and geospatial considerations including fishing, shipping and nature conservation, alongside continued stakeholder engagement.

5. Recommendations to enhance the evidence base to support future decisions

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5. Recommendations to enhance the evidence base to support future decisions

The analysis illustrates the most influential factors that will affect the location and cost of future offshore wind in UK waters.

However, there are still unknowns, uncertainty and gaps in the evidence base, and different assumptions could create a different picture. Key areas should be further developed to enable the optimal deployment of offshore wind in a net zero energy system.

We propose the following next steps to help BEIS, The Crown Estate and Crown Estate Scotland, as well as the broader industry and stakeholders, establish an increasingly robust evidence base to inform decisions.

Integration and assessment of broader system factors through whole-system planning

This project has focused on the offshore aspects of delivering offshore wind, assuming radial connections of projects largely within the current regulatory charging system.

The holistic network design exercise being carried out in parallel to this study, as part of the OTNR, considers the strategic onshore and offshore infrastructure required to meet the 2030 target for offshore wind and support net zero for 2050, identifying opportunities for coordinated infrastructure and minimising cumulative impacts on the environment and communities.

The outcomes of this study could affect the distribution of offshore wind in the future, making it more cost-effective to locate in some areas over other. This could significantly change the picture presented in this analysis.

The locations of these coordinated grid hubs will affect the distribution of offshore wind, making it more cost-effective to locate near these connection points. This could significantly change the picture.

Other studies have demonstrated the system benefits of geographical distribution of offshore wind. Encouraging regional spread of wind farm locations can support energy security and supply chain jobs, and create investment opportunities, while recognising areas that provide a good balance between energy costs and the complex interactions with other seabed activities and environmental considerations.

Whole-system planning is necessary to integrate the understanding from this work and to build a picture of the optimal energy system.

An initial step following completion of the current OTNR scope could be bringing together these two studies, incorporating the findings from each and identifying the next steps to build a more complete, whole-system view.

Integrated marine spatial planning, supported by further data gathering to improve quality of existing datasets

A net zero offshore wind deployment represents a step change in the rate of deployment and growth of the industry. Balancing the interactions of multiple sea activities and environmental sites will be increasingly critical to economically sustainable offshore wind deployment. Whole-system planning, as well as exploration of co-location and co-existence opportunities, should be integrated with marine spatial planning to improve decision-making.

In some areas, improving the quality and reliability of the datasets used to inform strategic decisions, particularly those related to nature conservation, will be critical. Suggestions of key datasets that could be further refined are outlined in Section 2.3, and include seabird foraging; fishing; CCS areas of interest; and coastal buffers for visual impact.

In addition, for some of the geospatial factors that are most influential on offshore wind deployment such as fishing, shipping and seabird foraging, using less conservative thresholds within the datasets would open up more options for marine spatial planning.

In other areas, the industry and UK Government will need to make pragmatic, evidence-based decisions on the relative priority of seabed uses.

5. Recommendations to enhance the evidence base to support future decisions

Continued stakeholder engagement and discussion of the balance between different activities

The evidence base established through this project presents a more detailed reference for discussion of the key geospatial influences, and where balance between these activities could be achieved.

To understand the optimal energy system, with the many other complex aspects in balance, will require deeper levels of interrogation and discussion of the interactions between offshore wind and other geospatial factors at a more granular level.

Further analysis of the range of spatial extents associated with different levels of activity within any one specific geospatial factor would build on the outputs of this study and support a deeper understanding of the balances.

Technology and supply chain investment

The outcomes of the analysis were that reducing costs, particularly in floating offshore wind technology, has a significant impact on what is developed, where and at what cost.

There are opportunities to reduce spatial planning conflicts, to offer geographical diversity and deliver low-cost renewable electricity through technology improvements, for example if floating wind installations combined with the associated transmission infrastructure can be realised in far-from-shore locations and at a pace that sees learning rates accelerate. However, these are currently future unknowns that can only be analysed today as a sensitivity.

Industry and the public sector must work together to support innovation and bring together existing and novel technologies to reduce costs.

Supply chain development offers a significant economic opportunity, driving green recovery, but the supply chain could also create a bottleneck in deployment, particularly if development is not geographically distributed.

Evaluating the capability of the local supply chain to deliver at the scale and rate required – coupled with the opportunity this presents for investment, skills and jobs – needs to be integrated into planning. This understanding should be built back into the integrated spatial and system planning.

6. Finding out more

6. Finding out more

For further information and to access the full range of model outputs associated with the final density cap model runs assessed as part of this study refer to:

www.futureoffshorewindscenarios.co.uk

This website provides access to the outputs of this study with user selection across the following key modelling parameters:

– Pathways

– Sensitivities

– Scenarios

An overview of the dashboard is shown in Figure 31. For further advice or questions relating to this study please contact OWECEnquiries@thecrownestate.co.uk.

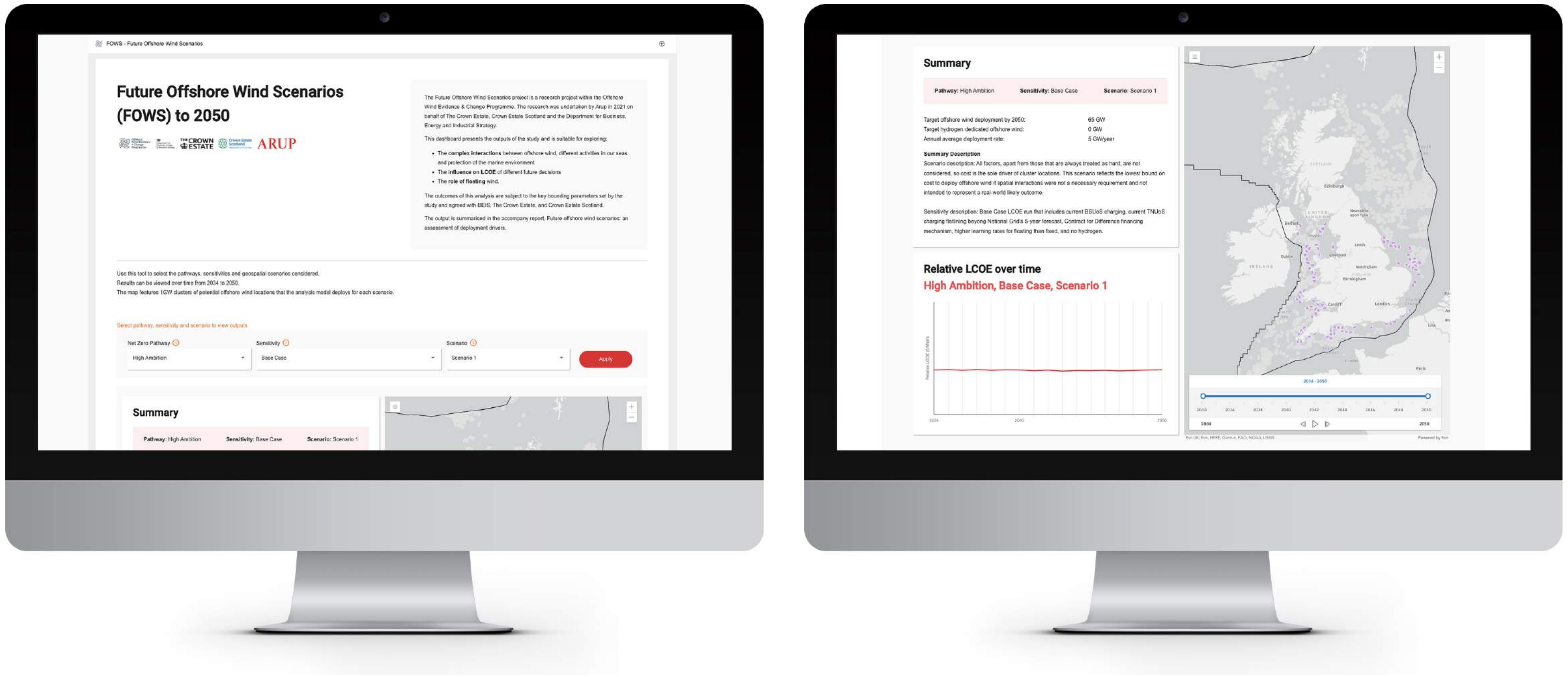

Figure 31.
Overview of the Future Offshore Wind Scenarios website and user selection options .

7. Acknowledgements

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7. Acknowledgements

We would like to extend appreciation and acknowledgement to all the organisations that were involved in shaping our analysis.

Particular thanks to the OWEC Steering Group Members and our Project Advisory Group Members (a subset of the OWEC group) for their integral role in the delivery of this analysis.

Further thanks go to the broad range of key stakeholders that provided their valuable input. This included over 100 participants across:

– Environmental / NGO groups
– Offshore wind developers
– Supply chain
– Industry bodies
– Trade bodies
– UK Government and devolved administration departments

8. Glossary

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8. Glossary

Acronym or Key Term	Description
AEP	Annual Energy Production
BEIS	Department for Business, Energy & Industrial Strategy
BGS	British Geological Survey
BSUoS	Balancing Services Use of System charges that reflects costs such as running the national control room, frequency response arrangements, and other ancillary services and constraint costs.
CAPEX	Capital Expenditure
CES	Crown Estate Scotland
CfD	Contract for Difference mechanism that supports project financing by reducing the WACC.
CTV	Crew Transfer Vessel
DECEX	Decommissioning Expenditure
DEVEX	Development Expenditure
EEZ	Exclusive Economic Zone
ESO	National Grid Electricity System Operator

Acronym or Key Term	Description
FEED	Front-End Engineering and Design
Hard geospatial factor	Geospatial layer over which offshore wind deployment is not allowed.
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
Not considered geospatial factor	Geospatial layer is not considered in the specific scenario and offshore wind can develop in these locations freely (not included in the loss function).
LCOE	Levelised Cost of Energy
Learning rates	Fractional reduction in the cost of LCOE components for each doubling of cumulative offshore wind capacity deployed.
Loss function	Summation of the normalised LCOE plus the normalised soft geospatial factor area for one cell.
MCZ	Marine Conservation Zone
MPA	Marine Protected Area

Acronym or Key Term	Description
Normalised LCOE	Processed values of LCOE where the cell with minimum LCOE has a value of 0 and the cell with maximum LCOE has a value of 1.
Normalised soft factor area	Processed values of soft factor area overlap where the cell with minimum area has a value of 0 and the cell with maximum area has a value of 1.
OPEX	Operational Expenditure
PEM	Polymer Electrolyte Membrane
SAC	Special Area of Conservation
Soft geospatial factor	Geospatial layer over which offshore wind deployment is allowed but balanced against areas of lowest LCOE.
SOV	Service Operation Vessel
SPA	Special Protected Areas
SSSI	Sites of Special Scientific Interest
TNUoS	Transmission Network Use of System charges that cover the building, operation and maintenance of the transmission system.
WACC	Weighted Average Cost of Capital

9. References

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9. References

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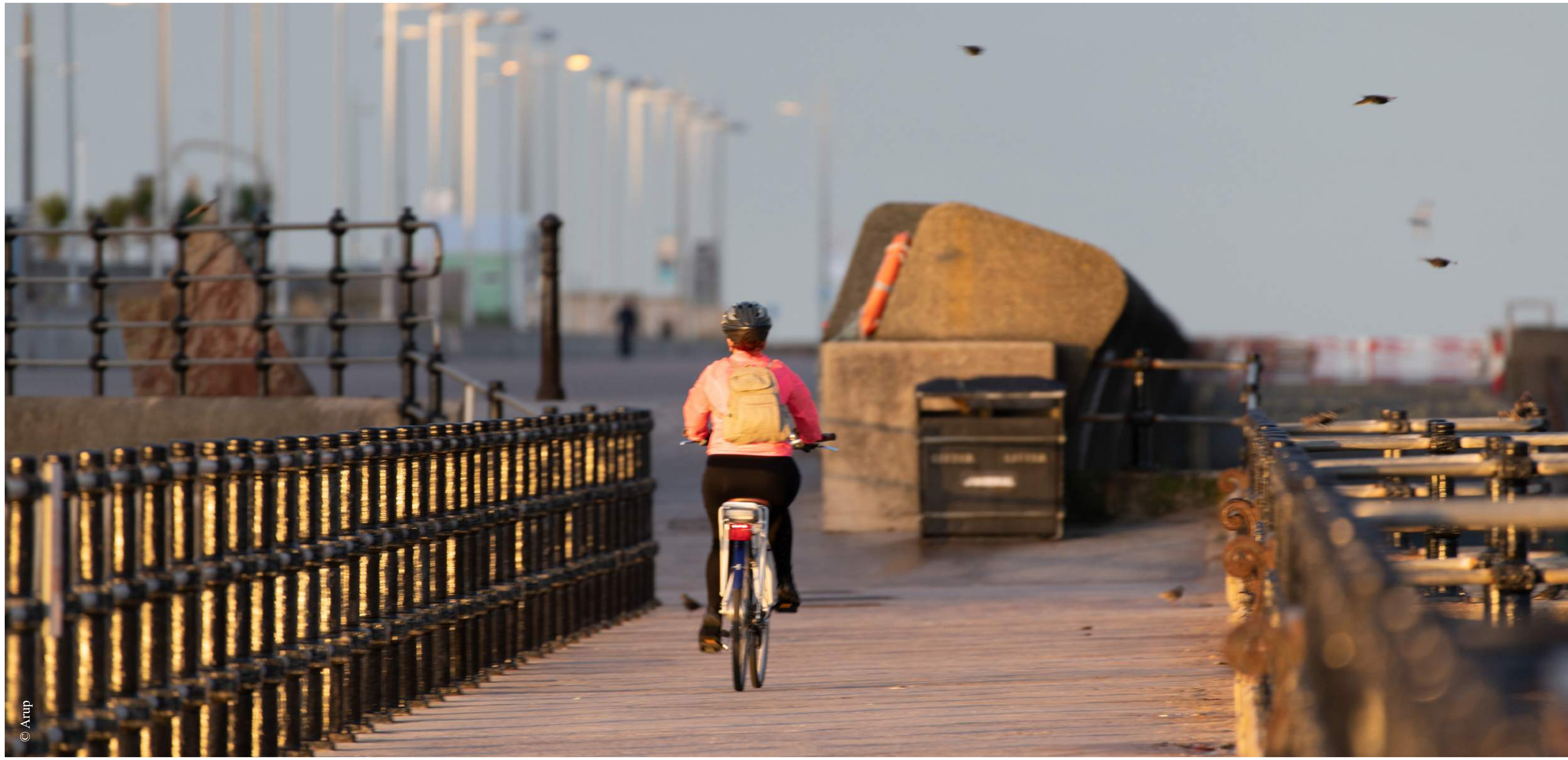
8. Transmission Network Use of System (TNUoS) Charges.
9. TUoS Statement of Charges.
10. Review and Update of Seascape and Visual Buffer study for Offshore Wind farms.



Appendix A
Data register

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
JNCC_SPA_5000	Special Protection Areas (SPAs)	This UK SPA layer contains the site boundaries and attribute information of SPAs designated in UK waters, both inshore and offshore, Last updated December 2020 - total number of sites - 123.	Designations	ESRI polygon shapefile	https://jncc.gov.uk/our-work/special-protection-areas-overview/	Open Government License v3.0	JNCC	
SNH_SSSI_Offshore	SSSI sites (Scotland)	Sites of Special Scientific Interest (SSSI) are those areas of land and water (to the seaward limits of local authority areas or MLWS) that Scottish Natural Heritage (SNH) considers to best represent our natural heritage. The national network of SSSIs in Scotland forms part of the wider GB series. SNH designates SSSIs under the Nature Conservation (Scotland) Act 2004. SSSIs are protected by law. SSSIs were first designated under the National Parks and Access to the Countryside Act 1949. The majority of these were later re-notified under the Wildlife and Countryside Act 1981. All 1981 Act SSSI designations are carried forward, and all new SSSI designations are now made, under the Nature Conservation (Scotland) Act 2004.	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/d64bf689-4ce8-465b-b00e-6a57dec94a22/site-of-special-scientific-interest-scotland	Open Government License v3.0	SNH	SSSIs were filtered to only include those that were situated on or near the coast and would therefore impact offshore development.
NRW_SSSI_Offshore	SSSI sites (Wales)	This spatial dataset contains the digital boundaries of Sites of Special Scientific Interest (SSSIs) in Wales. Local planning authorities are required to consult NRW before allowing any development to proceed that may affect an SSSI. Water, gas and electricity companies must also do the same. SSSIs have been designated, from 1949 to the present day, and are on-going. The data has been held digitally since the mid-1990s. This data has been checked by relevant NRW staff. Please refer to the designation map as the legal definitive boundary. For large SSSIs that were captured digitally and have been printed on a smaller scale map than OS MasterMap, please refer to the OS MasterMap edition at time of capture to view the definitive boundary.	Designations	ESRI polygon shapefile	https://lle.gov.wales/catalogue/item/ProtectedSitesSitesOfSpecialScientificInterest/?lang=en	© CNC/NRW All rights Reserved. Contains Ordnance Survey Data. Ordnance Survey Licence number 100019741. Crown Copyright and Database Right Data may be re-used under the terms of the Open Government Licence providing it is done so, acknowledging both the source and copyright of the owners. It is the recipient's responsibility to ensure the data is fit for the intended purpose.	NRW	SSSIs were filtered to only include those that were situated on or near the coast and would therefore impact offshore development.

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
NaturalEngland_SSSI_Offshore	SSSI sites (England)	A Site of Special Scientific Interest (SSSI) is the land notified as an SSSI under the Wildlife and Countryside Act (1981), as amended. Sites notified under the 1949 Act only are not included in the Data set. SSSI are the finest sites for wildlife and natural features in England, supporting many characteristic, rare and endangered species, habitats and natural features. The data do not include "proposed" sites. Boundaries are generally mapped against Ordnance Survey MasterMap.	Designations	ESRI polygon shapefile	https://naturalengland-defra.opendata.arcgis.com/datasets/f10cbb4425154b-fda349ccf493487a80_0	© Natural England copyright. Contains Ordnance Survey data © Crown copyright and database right [year].	Natural England	SSSIs were filtered to only include those that were situated on or near the coast and would therefore impact offshore development.
DAERA_ASSI_Offshore	ASSI sites (Northern Ireland SSSI equivalent)	Areas of Special Scientific Interest (ASSI) provide statutory protection for the best examples of Northern Ireland's flora, fauna, geological or physiographical features.	Designations	ESRI polygon shapefile	https://www.opendatani.gov.uk/dataset/areas-of-special-scientific-interest	"©NIEA, 2019 ASSI is licensed under the Open Government Licence: http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/ "	NIEA	SSSIs were filtered to only include those that were situated on or near the coast and would therefore impact offshore development.
JNCC_Ramsar	UK Ramsar sites	A spatial dataset of Ramsar sites in the United Kingdom. The dataset does not include sites in the UK's Overseas Territories and Crown Dependencies. Ramsar sites are wetlands of international importance designated under the Ramsar Convention. Ramsar sites are submitted to the Ramsar Secretariat by JNCC on behalf of the UK Government.	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/acc63c60-0850-49a9-afce-88d58cd1a1b2/ramsar-sites	Open Government License v3.0	DEFRA	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
EEA_Natura2000_UKEEZ_Offshore	UK Natura 2000 sites	"Natura 2000 is an ecological network for the EU composed of sites designated under the Birds Directive (Special Protection Areas or SPAs) and the Habitats Directive (Sites of Community Importance or SCIs, and Special Areas of Conservation or SACs). The European database of Natura 2000 sites consists of a compilation of the data submitted by the Member States of the European Union. This European database is generally updated once a year to take into account any updating of national databases by Member States. "	Designations	ESRI polygon shapefile	http://ec.europa.eu/environment/nature/natura2000/db_gis/index_en.htm#sites	"No limitations to public access. There are specific terms and conditions relating to the use of downloaded boundary data within the United Kingdom. If you intend to use the UK data you must first agree to the end user licence http://www.jncc.gov.uk/page-5232."	European Environment Agency	
IMO_Traffic_Separation_Schemes	Traffic Separation Schemes	"UK EEZ Ships' Routeing Measures as approved by the International Maritime Organisation (IMO), and/or the Maritime and Coastguard Agency (MCA) (as National Competent Authority). A Traffic Separation Scheme is an area in the sea where navigation of ships is highly regulated. It is meant to create lanes in the water and ships in a specific lane are all going in (roughly) the same direction. A TSS is created in locations with dense shipping where ships can go in different directions and where there is a high risk of collisions. "	Navigation	ESRI polygon shapefile	https://data.gov.uk/dataset/67ae3ef7-22da-45a8-8be8-306ce5798161/traffic-separation-schemes	"Open Government License v3.0 The data sets are not suitable for use in marine navigation or in the creation of navigational products."	UK Hydrographic Office	
TCE_AnchorageAreas_ply	Anchorage Areas	Areas designated as permanent anchorage areas.	Navigation	ESRI polygon shapefile	OceanWise Marine Themes Dataset	TCE	TCE	Anchorage area polygons extracted from marine themes dataset and exported as a separate feature class for inclusion in the constraints analysis.

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
CEFAS_Dredge_Disposal	Dredge disposal sites	A GIS Shapefile showing the extents of the Licenced Disposal Sites for all of UK, including England, Wales, Scotland, Northern Ireland, Jersey, Guernsey and Isle Of Man.	Navigation	ESRI polygon shapefile	https://data.cefas.co.uk/view/407	Open Government License v3.0	CEFAS	
AIS_Density_Grid_2017_plus_STG678_only_gt600	High density shipping	"AIS density grid for 2017 processed by ABPmer on behalf of the MMO using AIS data supplied by the Maritime and Coastguard Agency (MCA), following a methodology previously developed by ABPmer under MMO project number 1066, entitled 'Mapping UK Shipping Density and Routes from AIS – Open Source Data and Methods'. This feature class contains the vessel density grid for the UK derived from the AIS_Transit_Lines_2017 dataset which used AIS data provided by the Maritime and Coastguard Agency (MCA). This feature class is limited to cells that contain >600 transits per year."	Navigation	ESRI polygon shapefile	https://abpmer.maps.arcgis.com/apps/webappviewer/index.html?id=59a2cde1b2914b36978f608eff806fbb	"AIS data published under Open Government Licence. Reproduced with permission of the MCA and MMO. © Crown Copyright. ABPmer 2019. © British Crown Copyright 2019. Open Government Licence reproduced with permission of the Marine Management Organisation."	ABPmer	"This dataset contains the average weekly shipping density for the whole of the UK at a 2km grid resolution. For 2017, AIS datasets were sampled from the first seven days of each month, commencing with January, at monthly intervals. The total value for all 12weeks was divided by 12to determine the weekly average, therefore decimal values may occur for certain cells. The weekly average was also multiplied by 52 to provide the estimated annual average. Ship type groups (STG): 6 - Passenger, 7 - Cargo, 8 - Tankers"

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
TCE_Oceanwise_NavigationalDredging_1000	Navigational Dredging	Areas where dredging for navigation purposes occurs. Included in the TCE OceanWise dataset.	Navigation	ESRI polygon shapefile	OceanWise Marine Themes Dataset	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	Features labelled as navigational dredging sites were extracted as an individual feature class from the OceanWise marine themes dataset.
CAA_Aerodromes_10000	Civil airports	Locations of major civil airports in the UK.	Aviation	ESRI point shapefile	https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/	2022 © Civil Aviation Authority	CAA	The shapefile was filtered to include only airports that were located within 10km of the coastline and therefore would potentially interfere with offshore wind development.
TCE_Minerals_Aggregates_Site_Agreements_1000	Minerals and aggregate extraction site agreements	This dataset represents all current marine aggregates sites in English, Welsh and Northern Irish waters. The two types of agreement are 'Production Agreement' and 'Exploration and Option Areas'. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Aggregates	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Evaporites_Agreements	Evaporites extraction site agreements	This dataset represents all current marine evaporates agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Aggregates	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Wind_Leasing_Round4_Preferred_Projects_5000	Round 4 wind leasing preferred project sites	This dataset represents the external boundary of the areas of seabed which have been awarded Preferred Project status through the Round 4 leasing process.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
TCE_Wind_Site_Agreements_5000	Existing wind site agreements	This dataset represents all current offshore wind farms in pre-planning, planning, construction and operational phases in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_FloatingOffshore-WindTestAndDemon-strationSites_5000	Floating offshore wind test and demo sites	The outlines for the three projects (The 100MW Whitecross project, located off the coast of Devon and Cornwall and the Llŷr 1 and Llŷr 2 projects, comprising two separate 100MW sites, each testing different technologies, located south of Pembroke, on the Welsh coast) were digitised.	Energy resource	ESRI polygon shapefile	Provided by TCE as shapefile	© The Crown Estate, 2022	TCE	
TCEScotland_Ener-gy_Infrastructure_Agreements_5000	Scottish energy infrastructure site agreements	Current designated energy and infrastructure site legal agreements in Scottish waters.	Energy resource	ESRI polygon shapefile	https://www.crown-estatescotland.com/resources/documents	Crown Estate Scotland data, created by Crown Estate Scot-land, 2019.	TCE Scot-land	
TCEScotland_Ener-gy_Infrastructure_Agreements_Cable-sAndPipelines_500	Scotland energy infrastructure cables and pipelines agreements	Current designated energy and infrastructure cable and pipeline area legal agreements in Scottish waters. Cables and pipelines were extracted from a wider dataset from designated sites.	Cables	ESRI polygon shapefile	https://www.crown-estatescotland.com/resources/documents	Crown Estate Scotland data, created by Crown Estate Scot-land, 2019.	TCE Scot-land	
TCES_Scot-land_CCS_Site	Scottish CCS Site	This dataset represents all current live CCS agreements in Scottish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents. This dataset was extracted from the TCE Scotland energy infrastructure agreements dataset.	Energy resource	ESRI polygon shapefile	https://www.crown-estatescotland.com/resources/documents	Crown Estate Scotland data, created by Crown Estate Scot-land, 2019.	TCE Scot-land	Extracted from larger Scottish Energy Infrastructure Agreements dataset.
TCE_Tidal_Stream_Site_Agreements_5000	Tidal stream site agreements	This dataset represents all current live tidal stream agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
TCE_Wave_Site_ Agreements_5000	Wave site agreements	This dataset represents all current live wave agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Natural_Gas_ Storage_Site_Agree-ments_500	Natural gas storage site agreements	This dataset represents all current live NGS agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Carbon_Cap-ture_and_Storage_ Site_Agreements	CCS site agreements	This dataset represents all current live CCS agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Natural_Gas_ Pipeline_Agree-ments_500	Natural Gas pipeline agreements	This dataset represents all current live NGS pipeline agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Energy resource	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
OGA_Infrastruc-ture_Platforms_Ac-tive_500m_Buffer	Active oil and gas platforms	This feature class was created by filtering the OGA Surface Infrastructure data set to show platforms with a status of active, pre-commission, or proposed. Platforms with status of abandoned or not in use were removed. The remainder of this metadata record refers to the metadata as provided by OGA.	Energy resource	ESRI polygon shapefile	https://www.ogauthority.co.uk/data-centre/oga-open-data/	OGA Open User Licence	OGA, NDR	
OGA_Fields	Oil and gas fields	Offshore field outlines as provided by the operators at the point of field determination or re-determination.	Energy resource	ESRI polygon shapefile	https://www.ogauthority.co.uk/data-centre/oga-open-data/	OGA Open User Licence	OGA, NDR	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
OGA_Pipelines_500	OGA pipelines	"The OGA used its powers under the Energy Act 2016 to require the reporting and disclosure of infrastructure and pipeline header data for the UKCS. The data was reported by UKCS infrastructure owners into the National Data Repository (NDR). The data set includes over 600 surface installations, nearly 4000 items of subsea infrastructure (everything from manifolds to individual wellheads), and over 3000 pipelines and umbilicals. "	Energy resource	ESRI polyline shapefile	https://www.ogauthority.co.uk/data-centre/oga-open-data/	OGA Open User Licence	OGA, NDR	
TCE_OceanWise_Hard-MilitaryPracticeAreas	Military practice areas (coastal firing ranges)	These are marine military practice areas considered to be hard constraints to offshore wind development. This consists primarily of coastal live firing ranges where no development is possible.	Navigation	ESRI polygon shapefile	OceanWise Marine Themes Dataset - https://www.oceanwise.eu/data/marine-themes/	© The Crown Estate 2022, © OceanWise 2022	TCE	Features labelled as military practice areas were extracted as an individual feature class from the OceanWise marine themes dataset. Coastal firing ranges were then extracted manually based on their location and appearance due to the data not having any indicator of what type of practice area the features are.

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
UKHO_Wrecks_50	Protected shipwrecks	Over 8,000 live and charted wrecks around the UK as maintained by the UKHO's Marine Geospatial Data Management team.	Navigation	ESRI point shapefile	https://www.admiralty.co.uk/digital-services/data-solutions/admiralty-marine-data-portal?gclid=CjwKCAiAgbiQBhAHEiwAuQ6Bkm0BoqbZCTTfXXv5aME1Zk4EdGw8NiWkrxpwWjIZisEUUQ_w9k-K1BoCetoQAvD_BwE	© Crown copyright 2022 UK Hydrographic Office	UKHO	
NuclearPowerStations_pt_10000	Nuclear power stations	UK nuclear power stations situated within 10km of the UK coastline	Energy resource	ESRI point shapefile	https://www.gov.uk/government/publications/map-of-nuclear-power-stations-in-the-uk	Open government license v3.0	Department f Energy and Climate Change	Station locations digitised as points from map published by Department of Energy & Climate Change.

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
JNCC_SAC	Special Areas of Conservation (SACs)	"JNCC collate information on SACs with marine components on behalf of the Country Nature Conservation Bodies (CNCBs) to create a dataset of inshore and offshore sites across the UK. This layer contains only the SACs that protect marine components and includes inshore and offshore sites. Special Areas of Conservation (SACs) with ""marine components"" protect habitat and/or species associated with the marine environment. Last updated May 2020. Total - 116 sites. More information on these SACs and the features that each SAC protects can be found in the SACs with marine components spreadsheet available here: https://hub.jncc.gov.uk/assets/598a60db-9323-4781-b5a8-dcf0ca3b29f9"	Designations	ESRI polygon shapefile		Re-use of the data is subject to the terms of the Open Government Licence v3.0 including attribution of the relevant copyright holders. http://www.nationalarchives.gov.uk/doc/open-government-licence/version/ The site boundaries include sections of UK Exclusive Economic Zone © Crown copyright. The exact limits of the EEZ are set out in The Exclusive Economic Zone Order 2013. Contains Joint Nature Conservation Committee data © copyright and database right [2020]. Contains Natural England data © copyright and database right [2020]. Contains NatureScot data © copyright and database right [2020]. Contains Natural Resource Wales data © copyright and database right [2020]. Contains Northern Ireland Environment Agency data © copyright and database right [2020]. Contains UK Hydrographic Office data © copyright and database right [2020]. Contains Ordnance Survey data © copyright and database right [2020].	JNCC	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
DAERA_MCZ	Marine Conservation Zones (MCZs) (Northern Ireland)	This layer shows Marine Conservation Zone boundaries designated within the Northern Ireland Inshore Marine Area.	Designations	ESRI polygon shapefile	https://www.daera-ni.gov.uk/articles/marine-conservation-zones	Open government license v3.0	DAERA	
NRW_MCZ	Marine Conservation Zones (MCZs) (Wales)	This spatial dataset contains the digital boundaries of Marine Conservation Zones (MCZs) former Marine Nature Reserves in Wales. MCZs are a way of conserving marine habitats and wildlife and other features, of special importance, along the shore or on the seabed. The Marine and Coastal Access Act 2009 allows for the creation of MCZs. MCZs protect a range of nationally important marine wildlife, habitats, geology and geomorphology, and can be designated anywhere in English and Welsh territorial and UK offshore waters.	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/29b7f-8da-3e10-4004-ba46-feeb-61599bfe/marine-conservation-zones-mcz	© CNC/NRW All rights Reserved. Contains Ordnance Survey Data. Ordnance Survey Licence number 100019741. Crown Copyright and Database Right Data may be re-used under the terms of the Open Government Licence providing it is done so, acknowledging both the source and copyright of the owners. It is the recipient's responsibility to ensure the data is fit for the intended purpose.	NRW	
NaturalEngland_MCZ	Marine Conservation Zones (MCZs) (England)	These are the boundaries for designated and recommended Marine Conservation Zones including the new tranche 3 consultation boundaries. Marine Conservation Zones are designated under the Marine and Coastal Access Act (2009). They protect nationally important marine wildlife, habitats, geology and geomorphology. The Marine Conservation Zone Project concerns the selection of MCZs in English inshore waters and offshore waters next to England, Wales and Northern Ireland. Sites will be selected to protect not just the rare and threatened, but the range of marine wildlife.	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/80c075c3-1880-44a0-bffc-69e20f307c21/marine-conservation-zones-england	Open government license v3.0 © Natural England copyright. Contains Ordnance Survey data © Crown copyright and database right 2022.	Natural England	

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GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
SNH_MPA	Marine Protected Areas (MPAs) (Scotland)	These are the boundaries of Marine Protected Areas (MPAs) network of Scotland	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/67572936-18dc-4180-af74-39b088b6fb19/nature-conservation-marine-protected-areas-mpa	© Crown Copyright, 2015. All rights reserved. License No. EK001-20140401. Not to be used for Navigation.	Scottish Government	
MS_Demonstration_Research_MPA	Demo and Research MPAs (Scotland)	The boundary of Demonstration and Research MPAs in Scotland.	Designations	ESRI polygon shapefile	https://data.gov.uk/dataset/fa6e0043-8ae5-4c41-ad7d-c0366779f13b/protected-sites-demonstration-and-research-marine-protected-areas-dr-mpa	"Open Government License (http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/) The following attribution statement must be used: Contains information from Scottish Government licensed under the Open Government Licence v3.0."	Scottish Government	
AIS_Density_Grid_2017_plus_STG678_only_gt200	Low density shipping	"AIS density grid for 2017 processed by ABPmer on behalf of the MMO using AIS data supplied by the Maritime and Coastguard Agency (MCA), following a methodology previously developed by ABPmer under MMO project number 1066, entitled 'Mapping UK Shipping Density and Routes from AIS – Open Source Data and Methods'. This feature class contains the vessel density grid for the UK derived from the AIS_Transit_Lines_2017 dataset which used AIS data provided by the Maritime and Coastguard Agency (MCA). This feature class is limited to cells that contain >200 transits per year."	Navigation	ESRI polygon shapefile	https://abpmer.maps.arcgis.com/apps/webappviewer/index.html?id=59a2cde1b2914b36978f608eff806fbb	"AIS data published under Open Government Licence. Reproduced with permission of the MCA and MMO. © Crown Copyright. ABPmer 2019. © British Crown Copyright 2019. Open Government Licence reproduced with permission of the Marine Management Organisation."	MMO	

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
AIS_Density_Grid_2017_plus_STG678_only_gt400	Medium Density Shipping	"AIS density grid for 2017 processed by ABPmer on behalf of the MMO using AIS data supplied by the Maritime and Coastguard Agency (MCA), following a methodology previously developed by ABPmer under MMO project number 1066, entitled 'Mapping UK Shipping Density and Routes from AIS – Open Source Data and Methods'. This feature class contains the vessel density grid for the UK derived from the AIS_Transit_Lines_2017 dataset which used AIS data provided by the Maritime and Coastguard Agency (MCA). This feature class is limited to cells that contain >400 transits per year."	Navigation	ESRI polygon shapefile	https://abpmer.maps.arcgis.com/apps/webappviewer/index.html?id=59a2cde1b2914b36978f608eff806fbb	"AIS data published under Open Government Licence. Reproduced with permission of the MCA and MMO. © Crown Copyright. ABPmer 2019. © British Crown Copyright 2019. Open Government Licence reproduced with permission of the Marine Management Organisation."	MMO	
TCE_Wind_Cable_Agreements_500	Wind site cable agreements	This dataset represents all current export cables for offshore wind farms in pre-planning, planning, construction and operational phases in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Cables	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Wave_Cable_Agreements_500	Wave site cable agreements	This dataset represents all current export cables for live wave agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Cables	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	
TCE_Tidal_Stream_Cable_Agreements_500	Tidal stream site cable agreements	This dataset represents all current export cables for live tidal stream agreements in English, Welsh and Northern Irish waters. The boundaries are a true reflection of what has been signed in the Agreements for Lease and Lease documents.	Cables	ESRI polygon shapefile	The Crown Estates Open Data portal at https://opendata-thecrownestate.opendata.arcgis.com/	© The Crown Estate, 2022 THE CROWN ESTATE OPEN DATA LICENCE (GIS) – VERSION 1.1	TCE	

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
Telecomms_500	Subsea telecomms cables	Telecomms cables extracted from SeaFish datasets provided by TCE.	Cables	ESRI polyline shapefile	https://www.seafish.org/safety-and-training/kingfisher-information-services/#z-download-datasets-for-fishing-plotters-3	© SeaFish, 2022, © The Crown Estate, 2022	TCE, SeaFish	Telecomms cables was an individual feature class in a wider SeaFish dataset.
BEIS_AOI_UKCoastline_13kmBuffer, BEIS_AOI_UKCoastline_18kmBuffer, ABPmer_SeascapeSensitivity_24km_Buffer, ABPmer_SeascapeSensitivity_30km_buffer, ABPmer_SeascapeSensitivty_40km_buffer	Coastal buffers	The range of considerations for FOWS meant a range of different coastal buffers (13, 18, 23, 30 and 40km) would be required to allow for different levels of development close to the coast depending on sensitivities. These coastal buffer datasets was created by buffering the dataset UK Coastline.	Navigation	ESRI polygon shapefile	Arup generated	n/a	Arup	
TCE_OceanWise_SoftMilitaryPracticeAreas	Marine military practice areas	These are marine military practice areas considered to be soft constraints to offshore wind development such as torpedo ranges.	Navigation	ESRI polygon shapefile	OceanWise Marine Themes Dataset - https://www.oceanwise.eu/data/marine-themes/	© The Crown Estate 2022, © OceanWise 2022	TCE, OceanWise	Features labelled as military practice areas were extracted as an individual feature class from the OceanWise marine themes dataset. Soft constraints were then extracted separately from the hard consideration coastal ranges.

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
NATS_HelicopterRoutes_Combined_3704	Helicopter routes	"The data show helicopter main routes digitised from the following NATS eAIS Package United Kingdom en-route charts: • Southern North Sea - Aberdeen ATSU (Anglia radar) area of responsibility and Anglia Offshore Safety Area (OSA) ENR 6-25 • Helicopter main routing indicators (HMRI) and northern North Sea off-shore safety area (OSA) ENR 6-26 • Aberdeen - Atlantic rim HMRI X-Ray/Yankee ENR 6-27 • Morecambe Bay/Liverpool Bay gas field helicopter support flights ENR 6-28 Publication date: 08 APR 2021"	Aviation	ESRI polyline shapefile	https://nats-uk.ead-it.com/cms-nats/opencms/en/Publications/AIP/Current-AIRAC/html/toc-frameset-en-GB.html	© ABPmer 2022 - The routes were digitised from georeferenced versions of the en-route charts, which cover large geographic areas. This coupled with a lack of reference points in offshore regions likely introduces a potential degree of error in the location of the routes; however routes were aligned with offshore platforms where these were identified in the en-route charts.	ABPmer, NATS	
NATS_Radar_200m_Offshore	Civil aviation radar 200m	"This file shows coverage of primary Surveillance Radar (PSR) cover at 200m therefore describing the areas where turbines of up to 200m height would be within line-of-sight of at least one of the primary surveillance radars operated or used by NATS En-Route."	Aviation	ESRI polygon shapefile	https://www.nats.aero/services-products/catalogue/n/wind-farms-self-assessment-maps/	© NATS 2022 - The data are provided for guidance only and do not affect the consultation requirements for formal planning applications set out in The Town and Country Planning (Safeguarded Aerodromes, Technical Sites and Military Explosive Storage Areas) Direction 2002; they are provided without prejudice and shall not affect NATS's statutory right to object to any formal planning application in respect of any proposed development. NATS accepts no liability for any costs, expenses or damages of any nature whatsoever incurred by any reliance on the data.	NATS	

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
OGA_CCS_High-PotentialAreas	Areas of high CCS potential	This dataset was provided by the OGA and shows indicative areas of the UK seabed with high potential for CCS development.	Energy resource	ESRI polygon shapefile	Sent directly from OGA as shapefile.	© Intellectual property and copyright 2022 Oil & Gas Authority	OGA	The raw data showed CCS potential against the OGA UK ocean blocks which are significantly larger than the hex cells of this study. The blocks were therefore spatially joined to the hex grid with cells situated in areas of high CCS potential being labelled as such.
TCE_CombinedAq-uacultureLeases	Aquaculture lease sites	Data showing live aquaculture lease sites in UK waters provided by TCE. This is a combined dataset combining two datasets provided by CES and TCE in order to cover the entire UK.	Navigation	ESRI polygon shapefile	"https://data.gov.uk/dataset/28c43af0-ed74-4072-bd5a-446a6da13fad/aquaculture-finfish-and-shellfish-farms-including-fishery-sites http://marine.gov.scot/maps/1229"	Open government license v3.0	TCE, CES	
RYA_AIS	Recreational sailing density	"Automatic Identification System (AIS) data to illustrate intensity of recreational boating activity within 12 nm of the UK coast. The values are a log10 taken of the total count of AIS intersections over three summer periods2011-2013within each 1 x 1 nm cell. They should be referenced on a scale of low to high intensity rather than by the absolute values. These are recorded as polygons."	Navigation	ESRI polygon shapefile	https://www.rya.org.uk/knowledge/planning-licensing/uk-coastal-atlas-of-recreational-boating	RYA and licensed users only	RYA	The RYA data was split into high, medium an low intensity areas which were used separately in the FOWS analysis.

Appendix A - Data register

GIS Layer Name	Consideration Name	Description / Relevance	Category	Data Type	Source	Licence	Provider	Notes/Processing
Seabird_ForageRange	Seabird foraging range scores	The data show the seabird foraging range score value per 2.5km hexagonal grid cell. The source data for the foraging range layer included SPA data for UK, Irish seabird colonies and European SPA sites. Species listed as assemblage species for an SPA were excluded in the score calculation.	Ecological receptors	ESRI polygon shapefile	Supplied by ABPmer as shapefile	© ABPmer 2022	ABPmer	The seabird foraging range scores ere broken down into decile groups.
Fishing_MMO_ ScotMap	Fishing activity - MMO and ScotMap combined	"This feature class contains the monetary values extracted from the MMO 2017 fishing activity and ScotMap datasets. Each grid cell contains the value from each source dataset and a summed value. The fishing data shows value of catch landed and is a combination of the MMO 2017 Fishing dataset which provides summaries of fishing activity for UK commercial fishing vessels of >15m in length and the ScotMap inshore fisheries mapping project data which provides a summary of fishing activity of Scottish registered commercial fishing vessels under 15m in overall length. Each grid cell contains the value from each source dataset (‘MMO’, ‘Scotmapl’) and the sum of these values in £ sterling."	Ecological receptors	ESRI polygon shapefile	"Scotmap - https://data.marine.gov.scot/dataset/scotmap-inshore-fisheries-mapping-scotland-recording-fishermen%E2%80%99s-use-sea MMO - https://www.gov.uk/government/collections/uk-sea-fisheries-annual-statistics"	"© ABPmer 2022 ScotMap: Scottish Government (Marine Scotland). © Crown Copyright, All rights reserved. MMO: Marine Management Organisation - Open Government Licence. Acknowledgement of the Marine Management Organisation is required."	ABPmer	Fishing activity was divided into decline groups before analysis. Cells that contain a value were ordered in terms of value and split into 10% groups. Each group was assigned a class value e.g. the 10% most valuable cells were assigned a class value of 10, the next 10% most valuable cells were assigned a class value of 9 etc. Cells that did not contain a value were assigned a class value of 0.

Appendix B
Scenario definition

Appendix B - Scenario definition

Geospatial Factor	1	2	3	4	5	6	7	8	9	10
Existing wind, wave, and tidal stream site agreements	H	H	H	H	H	H	H	H	H	H
Round 4 wind leasing preferred project sites	H	H	H	H	H	H	H	H	H	H
Floating offshore wind test and demonstration sites	H	H	H	H	H	H	H	H	H	H
Active oil and gas platforms	H	H	H	H	H	H	H	H	H	H
Natural gas storage site agreements	H	H	H	H	H	H	H	H	H	H
Carbon Capture and Storage site agreements	H	H	H	H	H	H	H	H	H	H
Nuclear power stations	H	H	H	H	H	H	H	H	H	H
Civil airports	H	H	H	H	H	H	H	H	H	H
Evaporites, and minerals and aggregate extraction site agreements	H	H	H	H	H	H	H	H	H	H
Navigational dredging	H	H	H	H	H	H	H	H	H	H
Dredge disposal sites	H	H	H	H	H	H	H	H	H	H
Military practice areas (coastal firing ranges)	H	H	H	H	H	H	H	H	H	H
Traffic Separation Schemes	H	H	H	H	H	H	H	H	H	H
Coastal buffer	N	H	H	H	H	H	H	H	H[1]	H
Fishing activity - MMO and ScotMap combined	N	S[2]	N	N	S	H	S	S	S	H
Shipping routes	N	S[3]	N	N	S	S	H	S	S	H
Seabird foraging range	N	S[4]	N	N	S	S	S	H	S	H
Special Protection Areas (SPAs)	N	S	S	H	S	S	S	H	S	H
Special Areas of Conservation (SACs)	N	N	S	H	S	S	S	H	S	H
Marine Conservation Zones (MCZs)	N	S	S	H	S	S	S	H	S	H
Marine Protected Areas (MPAs) including Demonstration and Research Areas	N	S	S	H	S	S	S	H	S	H

Geospatial Factor	1	2	3	4	5	6	7	8	9	10
1.5 nautical miles buffer around Traffic Separation Schemes	N	S	N	N	S	S	S	S	S	S
Anchorage areas	N	S	N	N	S	S	S	S	S	S
Marine military practice areas	N	S	N	N	S	S	S	S	S	S
9 nautical miles buffer around active oil and gas platforms	N	S	N	N	S	S	S	S	S	S
Civil aviation radar	N	S	N	N	S	S	S	S	S	S
Recreational sailing	N	S[5]	N	N	S	S	S	S	S	S
SSSI sites	N	N	N	N	N	N	N	N	N	N
Ramsar sites	N	N	N	N	N	N	N	N	N	N
Aquaculture lease sites	N	N	N	N	N	N	N	N	N	N
Helicopter routes	N	N	N	N	N	N	N	N	N	N
Natural Gas pipeline agreements	N	N	N	N	N	N	N	N	N	N
Oil and Gas Authority pipelines	N	N	N	N	N	N	N	N	N	N
Wind, wave, and tidal stream site cable agreements	N	N	N	N	N	N	N	N	N	N
Undersea telecommunication cables	N	N	N	N	N	N	N	N	N	N
Protected shipwrecks	N	N	N	N	N	N	N	N	N	N
Areas of high CCS potential	N	N	N	N	N	N	N	N	N	N

Key

H	Hard
S	Soft
N	Not considered

1. The coastal buffer was increased to 40km for Scenario 9, all other scenarios feature a 13km coastal buffer.
2. 60% of fishing activity landed value was taken for Scenario 2, all other scenarios feature 100% of landed value.
3. More than 200 transits per annum vessel density was taken for Scenario 2, all other scenarios feature an addition 3.5 nautical miles buffer.
4. High Intensity seabird foraging range was taken for Scenario 2, all other scenarios feature high and medium intensity datasets.
5. Moderate density recreational sailing areas were taken for Scenario 2, all other scenarios feature high density.

Appendix C
Detailed modelling output

Appendix C - Detailed modelling output

Net zero pathways

This study included three pathways to net zero by 2050. Overall offshore wind deployment ranged from 65 to 140GW, reflecting the uncertainty about what will be required to meet the future energy demand and the evolving Government targets as the industry continues to grow.

The results show that, across all the sensitivities and scenarios, changing the net zero pathway does not have a large impact on the average LCOE of the portfolio. Within one pathway, changes in the scenarios and sensitivities have a much more significant impact on the cost of the portfolio. Figure 32 illustrates this, showing the minimum, mean and maximum of the average portfolio LCOE for each pathway.

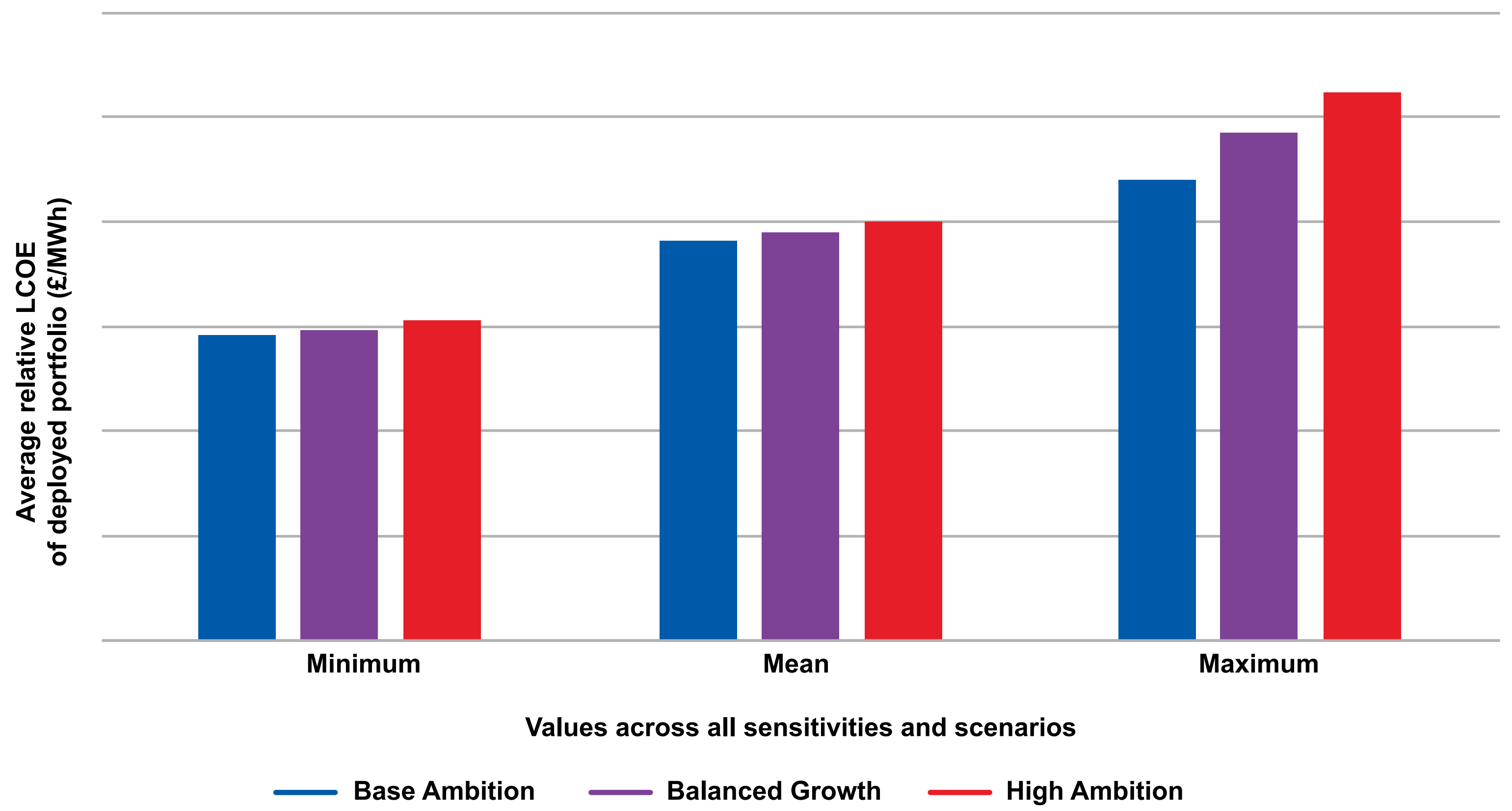

Figure 32.

Graph showing the average relative LCOE of the deployed portfolio for each net zero pathway for the scenarios leading the minimum, mean and maximum relative LCOE.

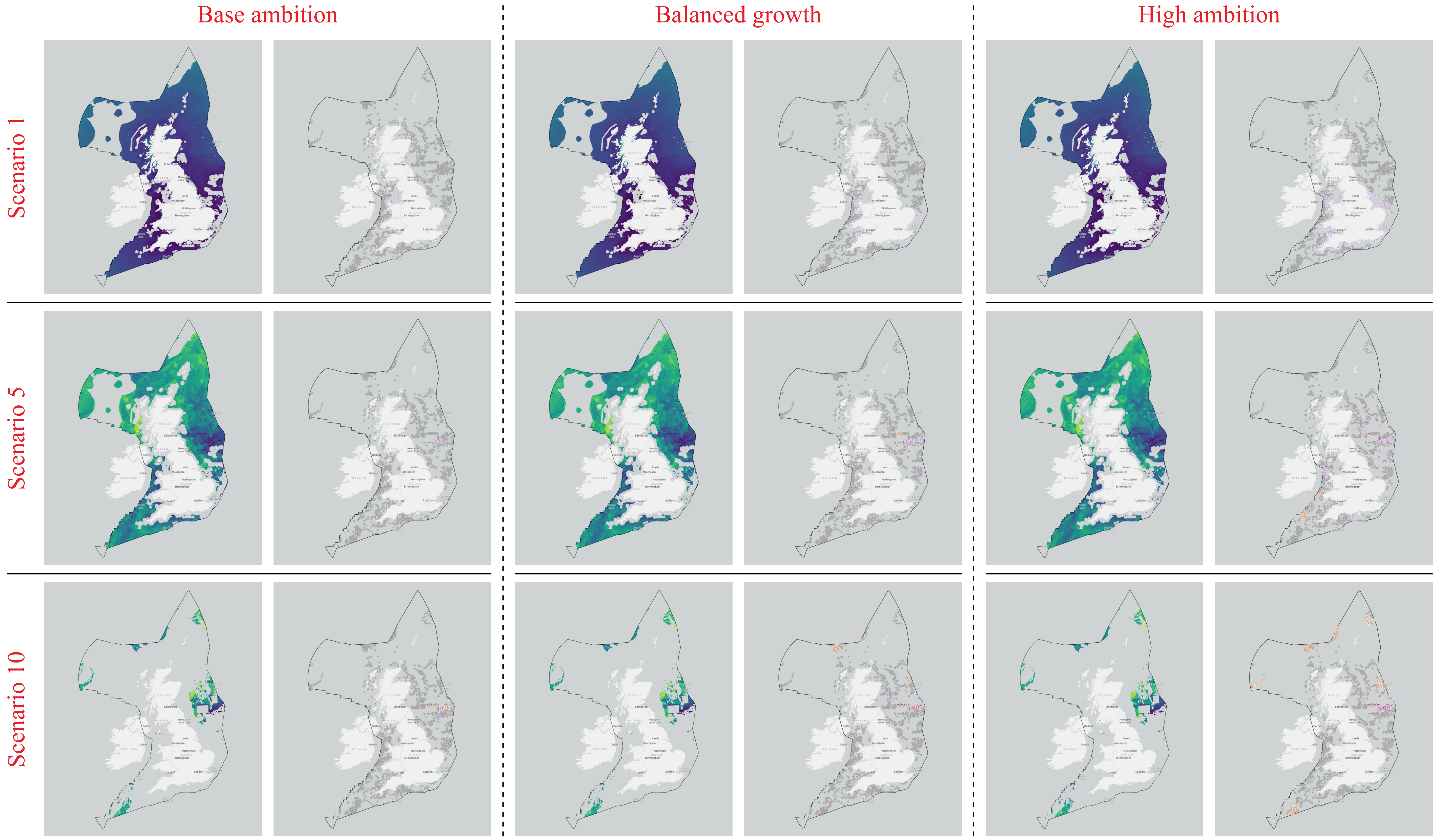

Figure 33.

Heatmaps and deployment model output showing the impact of the overall deployment target (as defined by the three net zero pathways) on the spatial distribution of clusters against three selected scenarios.

Appendix C - Detailed modelling output

The spatial distribution of offshore wind for a subset of scenarios displayed in Figure 33, shows that the clusters in the High Ambition pathway encompass those in the Balanced Growth pathway. Similarly, the locations in the Balanced Growth pathway also encompass those in the Base Ambition pathway. Therefore, for clarity, this report only presents results related to the High Ambition pathway. Output across all pathways can be viewed at:

www.futureoffshorewindscenarios.co.uk

Range of scenarios explored

Scenario 1 represents a theoretical lower bound case where only factors that will never be allowed to co-exist with offshore wind were treated as hard, and all others were not considered, allowing LCOE to be the sole location driver.

Result: deployment is as close to shore as possible, in southern UK waters where transmission charges are lowest.

In all the scenarios beyond this one, a minimum coastal buffer of 13km is introduced as hard, which pushes clusters further from shore.

Scenario 2 combined factors which had less than a 2% impact on LCOE when considered in isolation.

Result: When treated as soft, the LCOE increased by just under 10% compared with Scenario 1, highlighting the importance of integrated marine spatial planning.

In all scenarios beyond this one, this group of factors is always treated as soft.

Scenarios 3 and 4 evaluated how treating environmental designations as shown in Figure 16 as either soft or hard would affect deployment.

Result: The spatial distribution of clusters is relatively similar. When considering the group of environmental factors in isolation, completely avoiding them only results in a 3% increase of LCOE compared with allowing some co-existence with offshore wind.

Scenario 5 incorporates fishing, shipping and sensitive seabird foraging areas as soft factors, in addition to those already assumed in Scenarios 2 and 3.

Result: Modelling these factors in combination raises the LCOE by 15% compared with Scenario 1, as well as highlighting an area of the central North Sea which is relatively less constrained that deployment is drawn towards.

Scenarios 6, 7 and 8 examine the individual impact of completely avoiding co-existence with fishing, shipping and sensitive seabird foraging areas respectively.

Result: The area around the central North Sea still features strongly, but deployment in the Celtic Sea is prevented as the spatial extent of all three factors cover this area. LCOE increases by 20-24% compared with the lower bound in Scenario 1.

Scenario 9 replicates Scenario 5 but increases the hard coastal buffer from 13km to 40km.

Result: As would be expected, this results in the clusters originally located within the enlarged coastal buffer zone being deployed elsewhere.

Scenario 10 provided a theoretical upper bounding case incorporating fishing, shipping, sensitive seabird foraging areas and environmental designations treated as hard. It is effectively a combination of Scenarios 6, 7, and 8, resulting in the least area of seabed available for deployment.

Result: LCOE increases by almost 20% compared with Scenario 5, where those three factors are treated as soft instead. This scenario also sees a step change in the amount of floating wind deployed: up to 60%, compared with the next highest value of 45% seen in Scenario 8.

Appendix C - Detailed modelling output

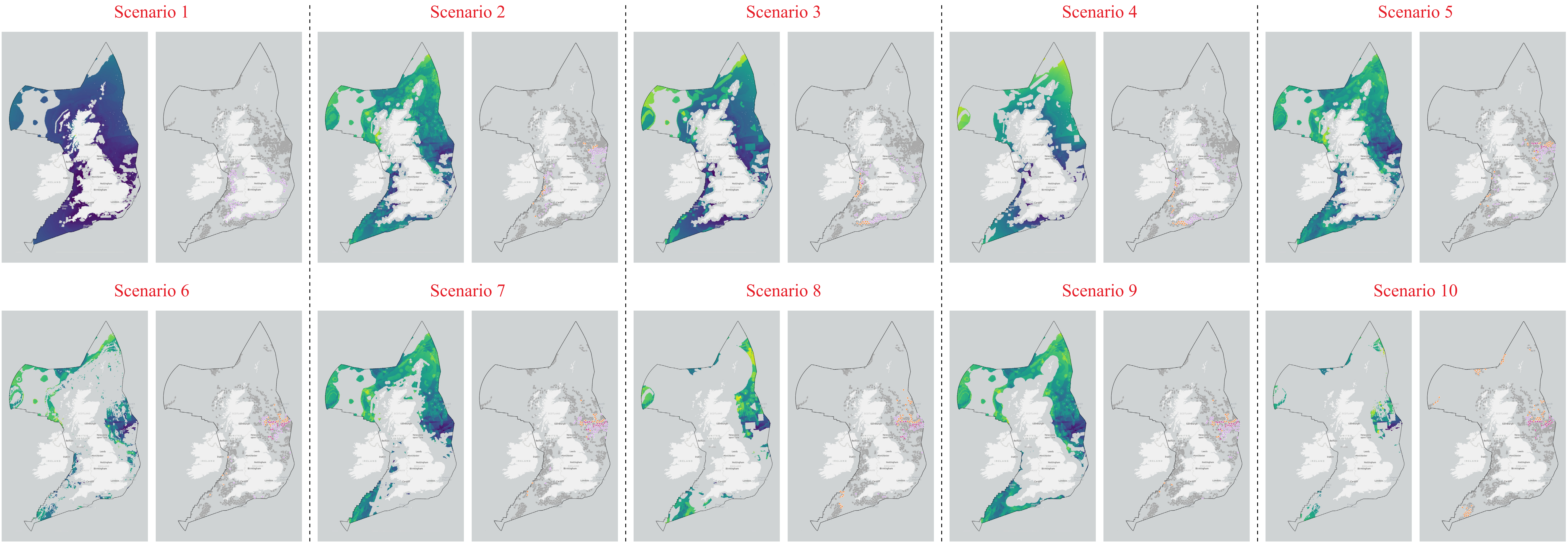

Figure 34.
Heatmaps and deployment model output showing the range of scenarios 1-10 for Base Case (without density cap initial output).

Appendix C - Detailed modelling output

Density cap

In the scenarios that previously featured areas with a high concentration of clusters, mainly in the central North Sea region, including the density cap has the expected effect of dispersing this area – as seen in Figure 35. Deployment is shifted towards the next most attractive areas in terms of LCOE and overlap with geospatial factors.

This regional spread is most apparent in Scenario 5 onwards, where deployment is encouraged in Scottish and Celtic Sea waters compared to the model output without the density cap. The dispersion effect is less apparent in the most constrained scenario, Scenario 10, because of the small area of seabed available for deployment.

The amount of floating wind deployed fluctuated in some of the individual scenarios after introducing the density cap, however the minimum (0%), mean (15%) and maximum (70%) contribution of floating wind to the total deployed portfolio across all the model runs remained within the same range as without the density cap. Despite this variation, the portfolio LCOE varied by less than 1% on average across scenarios when comparing the cost with and without density cap, due to floating wind achieving cost parity with fixed foundations generally by the late 2030s in the model.

The widest spread in regional deployment observed across all the modelling outputs resulted from combining the density cap with the sensitivity where TNUoS is removed, as shown in Figure 36. Similar patterns can be seen in the impact of including the density cap on LCOE and floating contribution as in the Base Case.

The almost negligible impact on LCOE of a wider regional spread in the cluster locations also highlights that there are many areas of the UK waters that are similarly suitable for offshore wind deployment, based on the assumptions used in this research exercise. Decisions regarding future offshore wind policies therefore need to approach marine spatial planning considering the energy system as a whole. Achieving this could unlock potential for cost-effective offshore wind at a scale beyond the 140GW of the High Ambition pathway.

Appendix C - Detailed modelling output

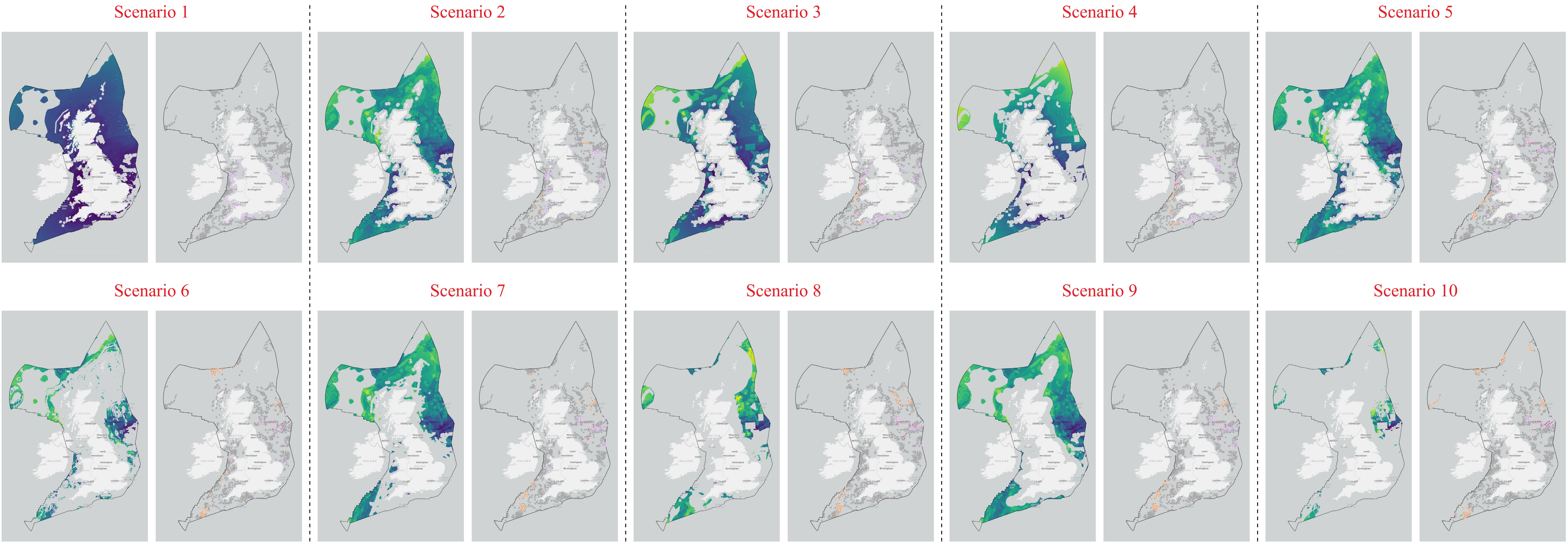

Figure 35.
Heatmaps and deployment model output showing the range of scenarios 1-10 for Base Case with the density cap incorporated (final output).

Appendix C - Detailed modelling output

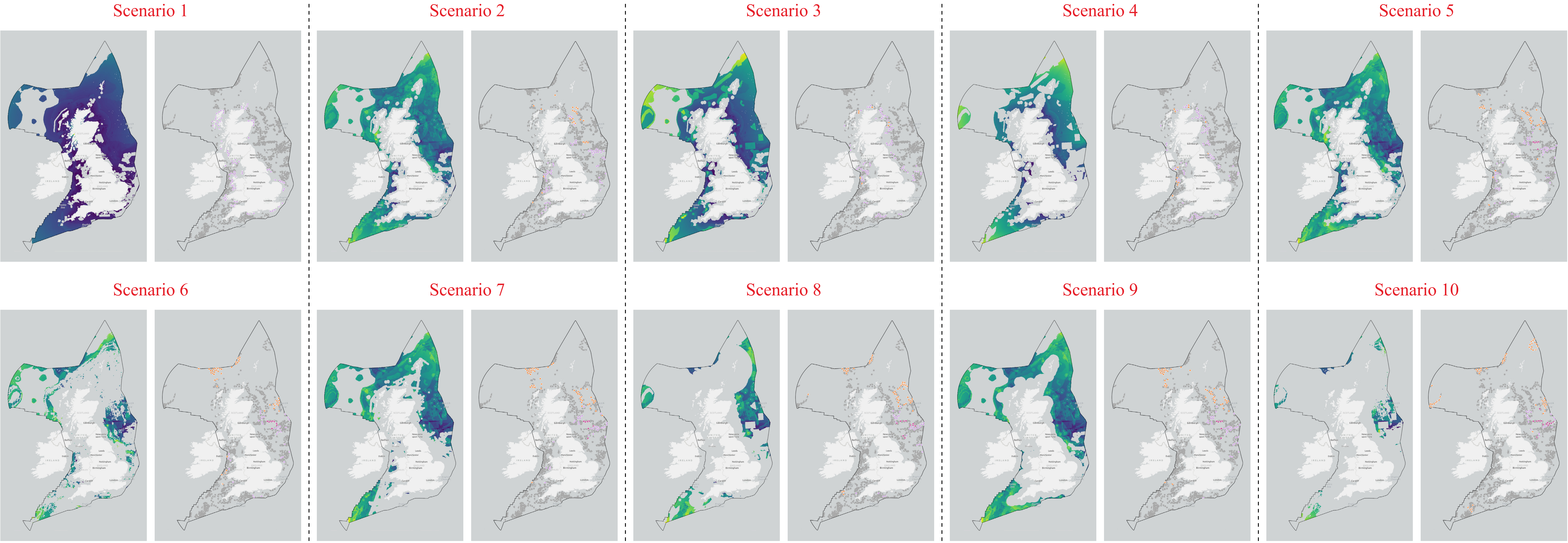

Figure 36.

Heatmaps and deployment model output showing the range of scenarios 1-10 for no TNUoS sensitivity with the density cap incorporated (final output).

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