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Finding space for offshore wind to support net zero: A methodology to assess spatial constraints and future scenarios, illustrated by a UK case study

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ABSTRACT

Government and commercial forecasts indicate global ambitions for 2000 GW of installed offshore wind (OW) by 2050 to meet the targets of the Paris Agreement. Set against a current global installed capacity of 56 GW offshore wind, which has taken over 30 years to achieve, the challenge of installing 35 times that capacity in the coming 30 years is considerable. Aside from the issue of the necessary pace of OW installation, another challenge is scale: Where in the ocean could and should this new infrastructure be placed? This paper presents a spatial analysis approach for assessing the location of future offshore wind that collates and integrates, metocean, geoscience, ecological and anthropogenic features and intersects with engineering requirements. A new contribution to the field is made through calibration in relation to current ocean 'crowdedness', which leads to a suitability ranking of new sea regions. A case study is presented to illustrate the workflow and methodology of this approach based on the United Kingdom (UK)-Economic Exclusive Zone (EEZ). The UK has been selected as an exemplar due to its well-developed offshore wind sector, having the greatest installed capacity globally until the close of 2021, and as a region with ambitious and legislated offshore wind targets to meet net zero. The modelling and analysis quantify the need to eliminate the water depth barrier through floating OW technology, open up new sea regions and the associated port and grid infrastructure, as well as to assess the potential impact of increased utilisation of ocean space for OW.

1. Introduction

1.1. Growth of offshore wind

The Global Offshore Wind Energy Compact proposes a global target of 2000 GW installed capacity of offshore wind (OW) by 2050 to meet the Paris Agreement [1,2]. This corresponds to a 35-fold increase compared to current capacity and requires an installation rate of 70–80 GW annually between now and the mid-century. This requires around 5000 new turbines installed each year occupying more than 500,000 km^2 of ocean by 2050.

Experience of OW, and ambitions and targets for OW growth, vary across the globe. The commercial OW sector emerged in Europe following the 1991 commissioning of the first OW farm, Vindeby, in Denmark [3]. China has led in OW installations in most recent years (2018–2021), and now hosts nearly half of the global installed OW capacity, with the other half spread across Europe [4]. Europe is forecast to remain a strong region for OW, with the European Union targeting 340 GW of offshore renewable energy by 2050 [5]. The United Kingdom (UK), which has the most OW capacity in Europe, has set targets for 50 GW by 2030 [6]. China is forecast to continue dominating the Asia market, with targets for an additional 40–50 GW of OW in 2021–2025 set out in its 14th 5-year plan [7] and independent forecasts indicating close to 100 GW of installed capacity by 2030 [4]. Vietnam, Taiwan, South Korea, Japan, and India also have ambitious targets, totalling more than 70 GW of installed OW capacity by 2030 [4].

The pace and scale of OW growth, however, must be balanced with protection of ocean ecology, heritage sites and co-existence with other economic and social activities. This balance is critical if the blue economy is to play a sustainable part in our shared future [8] and must be publicly evident to ensure social acceptance. To keep this balance during unprecedented OW growth, robust spatial planning that considers all constraints, both natural and anthropogenic, is needed (e.g., [9–11]).

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Nomenclature

List of Abbreviations

AcW	Layer of active well sites
Ag	Layer of aggregates sites
An	Layer of anchorage areas
Aq	Layer of aquaculture sites
C	Layer of cables
CCS	Layer of carbon capture storage
Dr	Layer of dredging sites
DSR	Layer of deep sea reservation
ED50	European datum 1950
EEZ	Exclusive economic zone
Fi	Layer of fishing sites
FNS	Layer of fishing spawning & nursery grounds for selected fish
GIS	Geographic informationsystem
GmF	Layer of geomorphology features
HbA	Layer of harbour areas & facilities
HrC	Layer of heritage coastline
IEE	Institut für Energiewirtschaft und Energiesystemtechnik
IMOR	Layer of international maritime organisation routes
IRENA	International Renewable Energy Agency
MCZ	Layer of marine conservation zone
Mlt	Layer of Ministry of Defence sites
MM	Layer of mineral mining sites
NaB	Layer of area of natural beauty
NATS	National air traffic services
Nav	Layer of navigational points
NRn	Layer of non-renewable energy sites
OnGca2050	Layer of oil and gas fields ceased after 2050 & infrastructures/pipelines
OnGcb2050	Layer of oil and gas fields ceased after 2050 & infrastructures/pipelines
OSPAR	Oslo and Paris convention
OST	Layer of OSPAR threatened species
OW	Offshore wind
PW	Layer of protected wrecks
Ra	Layer of NATS-high radar interference
Rn	Layer of renewable energy sites
SAC	Layer of special areas of conservation
SbO	Layer of seabed obstructions
SL	Layer of submarine landscape
Slp	Layer of steep slope zone
SPA	Layer of special protection area
SSSI	Layer of site of specific scientific interest
SuW	Layer of suspended well sites
TCE	The Crown Estate
UK	United Kingdom
UTM	Universal Transverse Mercator
VR	Layer of vessel routes
WD	Layer of waste disposal sites

List of Symbols and Units

$\bar{v}_{110m}$	30-year-average of wind speed at 110 m hub height (m/s)
A_{agg_AC}	total aggregate space of all anthropogenic layer (km^2)
A_{agg_EC}	total aggregate space of all ecological layer (km^2)
A_{agg_GC}	total aggregate space of all geological layer (km^2)
$A_{av\_up\ to\ equally\ crowded}$	total space available of clear water, less crowded, and equally crowded space (km^2)
$A_{av\_up\ to\ less\ crowded}$	total space available of clear water and less crowded space (km^2)
A_{ex}	approximation of total extra space required to fulfil the selected net zero scenario (km^2)
D_r	rotor diameter (m)
$Mdn_{\rho,S=10D_r}$	median of ρ where $S = 10D_r$ from 2020 to 2050 (MW/km^2)
$Mdn_{\rho,S=8D_r}$	median of ρ where $S = 8D_r$ from 2020 to 2050 (MW/km^2)
$Mdn_{\rho,S=9D_r}$	median of ρ where $S = 9D_r$ from 2020 to 2050 (MW/km^2)
P_{ex}	extra additional OW power capacity required to fulfil the selected net zero scenario (GW)
$P_{existing}$	total OW power capacity that recentlycurrently exist in the UK-EEZ waters (GW)
P_{leased}	total OW power capacity that is estimated can be produced from the current OW leased sites (GW)
P_{2030}	total OW power capacity target by 2030 to fulfil the selected net zero scenario (GW)
P_{2050}	total OW power capacity target by 2050 to fulfil the selected net zero scenario (GW)
rA_{ex}	approximate total extra space required as multiple of current OW leased sites (km^2)
$\bar{s}$	average of distance to shore in each specified site (m)
s_{90}	90th percentile of distance to shore data of selected area (m)
$\bar{z}$	average of water depth in each specified site (m)
z_{90}	90th percentile of water depth of specified site (m)
$\rho_{S=10D_r}$	power density of OW farm assuming that the spatial distance between turbines is equal to 10 x rotor diameter,D_r (MW/km^2)
$\rho_{S=8D_r}$	power density of OW farm assuming that the spatial distance between turbines is equal to 8 x rotor diameter,D_r (MW/km^2)
$\rho_{S=9D_r}$	power density of OW farm assuming that the spatial distance between turbines is equal to 9 x rotor diameter, D_r (MW/km^2)
ΔP	OW power capacity per year (GW)
A	total space (km^2)
P	OW power capacity (GW)
S	minimum turbine spacing (m)
p	turbine nameplate power (MW)
s	distance from shore (km)
y	year
z	water depth (m)
ρ	power density of OW farm (MW/km^2)

Implementation of these spatial constraints in OW planning may limit the wind resources that can be harnessed in certain regions (e.g., [9, 12]), and could shape the rate and manner in which net zero is reached.

In this paper, an integrated approach to marine spatial planning for future OW is illustrated through a case study of the UK Exclusive Economic Zone (EEZ). The UK has been selected for this study due to its high existing OW capacity [4] diverse seabed and metocean conditions, rich and varied ecosystems, and congested ocean space that creates constraints from other ocean uses. The UK-EEZ is an area with established OW farms and a complex and challenging environment for planning future OW developments. This provides an opportunity to calibrate the levels of constraint, co-location, and co-usage at existing OW sites – referred to as their 'crowdedness' – and then use this measure to assess the available ocean space for future OW. This approach can be applied to any other region across the globe.

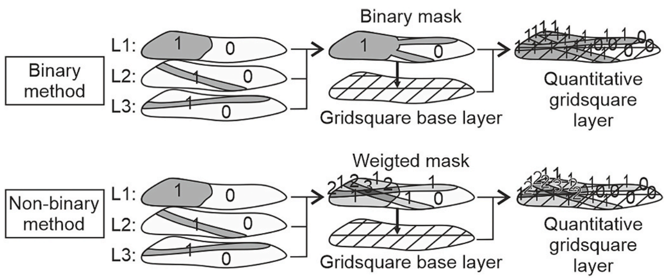


Fig. 1. Illustration of binary and non-binary method to result in a quantitative layer.

1.2. Space availability assessment for offshore wind

Two methods are commonly used to define space availability for OW, both reliant on use of geographical information systems (GIS): (i) a binary mask to determine *go* and *no-go* space for OW (e.g., [9,13]) or (ii) a weighted mask to assign a non-binary value for each space, dependent on its characteristics (e.g., [14,15]) (See Fig. 1 for an illustration for each). Each of these methods has limitations. The binary mask method is simple to conduct and objective in implementation, determining an available space based on clear and common agreed constraints such as regulations, and leads to *go* and *no-go* regions. However, this binary method oversimplifies the complexities of marine space where some level of co-location or co-usage maybe acceptable and where impact may occur from interactions between separate constraints. These complexities are better captured by non-binary masks that are combined with a weighting factor to generate a synthetic map of suitability. The weighted mask method, however, depends on the subjective judgement of experts to determine the appropriate weights combined to create the suitability value [16,17]. To capture to the strengths of both methods recent studies (e.g., [18,19]) have combined these approaches.

There are a range of methods that can be used to generate the non-binary mask [19]. Each method sets out a different rule to generate the weight for each criteria (referred to here as the *variable*). The weight for each variable is summed to determine an overall value, which in turn is used to define and rank the suitability level for OW. The most frequently used method is the analytical hierarchy process (AHP), which applies a mathematical model to assign a weight for each variable and the attributes based on pairwise comparisons between variables and attributes [14,18,20]. In some studies, AHP is combined with other methods to reduce the uncertainty or subjectivity of the methods (e.g., with evidence reasoning (ER) [20,21] or with fuzzy sets solution [22,23]).

A more straightforward method that disregards the complex interactions between variables is simple additive weighting (SAW). SAW directly assigns weights without pairwise comparison to each variable before totalling [20,24]. Critically these non-binary mask methods require expert opinion to judge the relative importance of each variable/attribute, and the importance may vary with time and among different stakeholders. This process, however, mirrors discussions between developers and regulators throughout environmental impact assessment and allows scope for weighting to be varied dependent on national and local requirements.

In this study, a combined binary and alternative non-binary mask is applied to determine areas suitable for future OW. The alternative non-binary mask is drawn from a SAW method that sums the total weight given from the variables defined as constraints existing in each space, where all variables are weighted equally. This method does not aim to identify and assess the relative importance of variables to OW development, but rather to assess the crowdedness level from the variables existing in each space. This value indicates the challenges that would be encountered in working in a given area, as well as allowing direct comparison to other areas and extant OW locations. A lower number of variables indicates the lower potential for conflict between stakeholders, regulations, or design constraints.

A particular contribution of this study is that the number of constraints in the area of current OW leased sites has been assessed, across all of the leasing rounds in the UK to date. This provides an indication of the 'crowdedness' level that is accepted at current OW developments. This is useful because it gives a basis to assess the likely suitability of other sea regions for future OW development. It is therefore possible to estimate the ocean space suitable for OW in each sea region, allowing for other ocean uses and constraints, which is then compared with the space required to meet net zero targets. The list of constraints for OW development used in this study is drawn from the review of more than 70 GIS studies of offshore wind worldwide from year 2001–2021, as described in Appendix A.1 and Supplementary Table 1 in Appendix A.2.

1.3. The UK context and previous assessments of potential sites for UK offshore wind

To meet current net zero targets, it has been forecast that the UK installed power capacity (P) of OW must increase to 65–473 GW by 2050, depending on the scenario chosen [25,26]. The less ambitious target ignores needs for growth and energy export, requiring 65–140 GW of OW to meet net zero, depending on societal and behavioural factors [25]. The most recent and ambitious targets range from 307 to 473 GW of OW to fulfil the UK's demands for electricity generation, hydrogen production and energy export (see Section 3). The range encompasses sub-scenarios in which OW forms different proportions of the renewable energy mix, with differing influences from societal and behavioural changes and from innovation [25]. Overall, these targets require the UK OW capacity to grow by a factor in the range of 6–50 from the current installed ~12 GW [27]. By reaching these targets the UK could contribute 5–25% of the global goal for 2000 GW of OW by 2050 [1].

Potential sites for OW in the UK-EEZ have previously been presented in academic papers, government, and industry reports. These sites are commonly derived from a space availability analysis that is further integrated with either economic (e.g., [12,18]) or technical feasibility (e.g., [16,28]). The availability of space is based on the presence or absence of constraints derived from natural or anthropogenic factors (such as the availability of adequate wind speed as a natural constraint, or shipping lanes as an anthropogenic constraint).

1.4. Contribution of this paper

The need to accelerate OW growth to achieve net zero makes integrated marine spatial planning increasingly important at a global level. However, there is a research lacuna with regards to how recent developments in net zero targets, wind turbine technology, windfarm planning and consenting, and marine spatial constraints can be integrated to quantify the challenge of marine spatial planning for future OW. This study into UK-EEZ availability for OW leverages four emergent opportunities specific to this region: (i) new perspectives created by rapid growth in OW targets, (ii) evolution in wind turbine specifications, now and in the coming decades, (iii) experience of planning and consenting from existing wind farms, and (iv) wide availability of marine spatial data.

We firstly assemble a new database of 34 feature layers that represent constraints relevant to OW development. We then combine these feature layers to quantify the spatial variability of constraints and 'crowdedness' across the UK-EEZ. Importantly, we calibrate these constraint levels against existing OW leases, to find thresholds of acceptability. This calibrated availability map shows the space available in each sea region for future OW. We then assess the ocean space required to meet net zero, allowing for the evolution of wind turbine technology. By comparing the available space and the required space for different net zero scenarios, we explore the potential for future

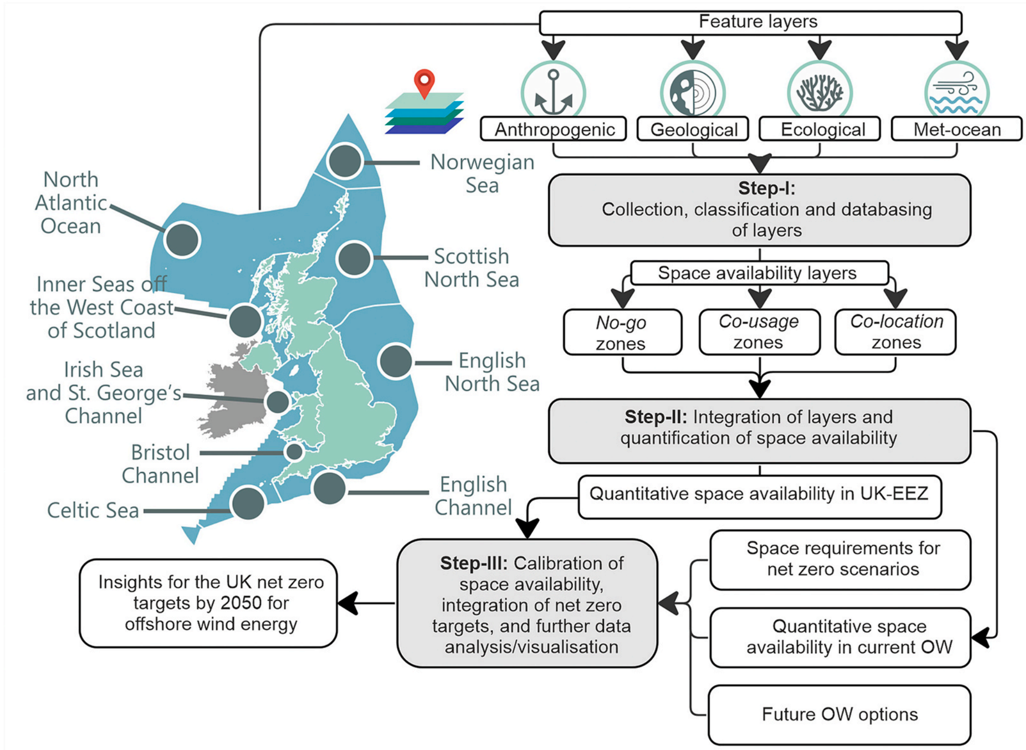


Fig. 2. Map of UK-EEZ waters and the outline of this study.

congestion, and the likely sea regions and ocean conditions that will be faced by future OW developments. This type of analysis has not been presented before and provides a method that can deployed across other regions. Cumulatively this will help to build a global picture of availability, crowdedness, and routes to mitigation on the road to net zero. In order to achieve this, we have also gathered a more comprehensive spatial dataset than previous studies[1] and presented this in an interactive dashboard[2] to allow the results to be explored online and freely accessed for further studies or assessments.

1.5. Structure of this paper

The structure of this paper follows the structure of the workflow and its cumulative outputs. It has been written in this way to make explicit the choices made at each step and aid reproducibility. This structure is reflected in Fig. 2. Section two sets out the method through which space availability was calculated. It details the contributing data (input layers), the derived layers and how they were created. Section three explores the space requirements associated with reaching net zero, by examining the evolution of wind turbine specifications and how this influences the energy produced per unit of ocean space.

Section four introduces the 34 feature layers, highlighting critical issues emergent from their construction and analysis. In section five these layers are utilised to divide ocean space into different categories of availability, combining a binary (available/unavailable) mask with a non-binary categorisation of crowdedness in available areas. In section six we calibrate the crowdedness scale based on existing wind farm leases, to identify thresholds of acceptable crowdedness for OW developments. These thresholds are used in section seven to set out the available space in each sea region of the UK-EEZ for future OW. Section eight then explores future scenarios of OW capacity in each sea region to meet different net zero scenarios.

2. Data sources and methodology

The following section sets out the processes through which data was ingested, harmonised and reclassified. Fig. 3 explicitly documents each step of this and following processes to enable replication of the method and application to other regions.

2.1. Sources and data management of the Initial Spatial dataset

A comprehensive set of 34 spatial layers representing different features and constraints forms the basis of the spatial analysis presented in this paper. Each layer is either publicly available or accessed through an academic license. The selection of these layers was based on requirements of current consenting processes, data used in comparable recent studies from academia and industry, as well as those dictated by the needs of the project described in this paper but not used elsewhere. The full list of layers used in both this study and other recent works is given in Appendix A.1. The list of layers, the constraints that they map, and the categorisations of each layer by feature type and availability for OW are described in Table .1. Further details including the data sources, data types, resolution (if applicable), the threshold used to define the constraint or usage as being active or applicable (i.e., mask area) as well as any further processing applied to the raw data are listed in Supplementary Table 2 in Appendix A.2.

The raw data used to generate each spatial layer originated in a variety of different vector and raster formats. All data were re-processed into vector polygons and combined within ArcGIS Pro 2.7 for harmonisation. Each dataset has its own spatial reference. To connect them all data was reprojected into European Datum 50, Universal Transverse Mercator 30 N (ED50 UTM 30 N). To generate the polygon layers multiple processing steps were required, varying between datasets. For

[1] See Supplementary Table.1 in Appendix A.2 for a full list of the datasets used here, and a comparison to the previous studies

[2] The interactive dashboards can be accessed at https://storymaps.arcgis.com/collections/3c485282571142f28de577b957a0b348 see Appendix A.3 for details. Animation demonstrating features and functionality of the interactive dashboards: https://youtu.be/J-6nFfxrCtE

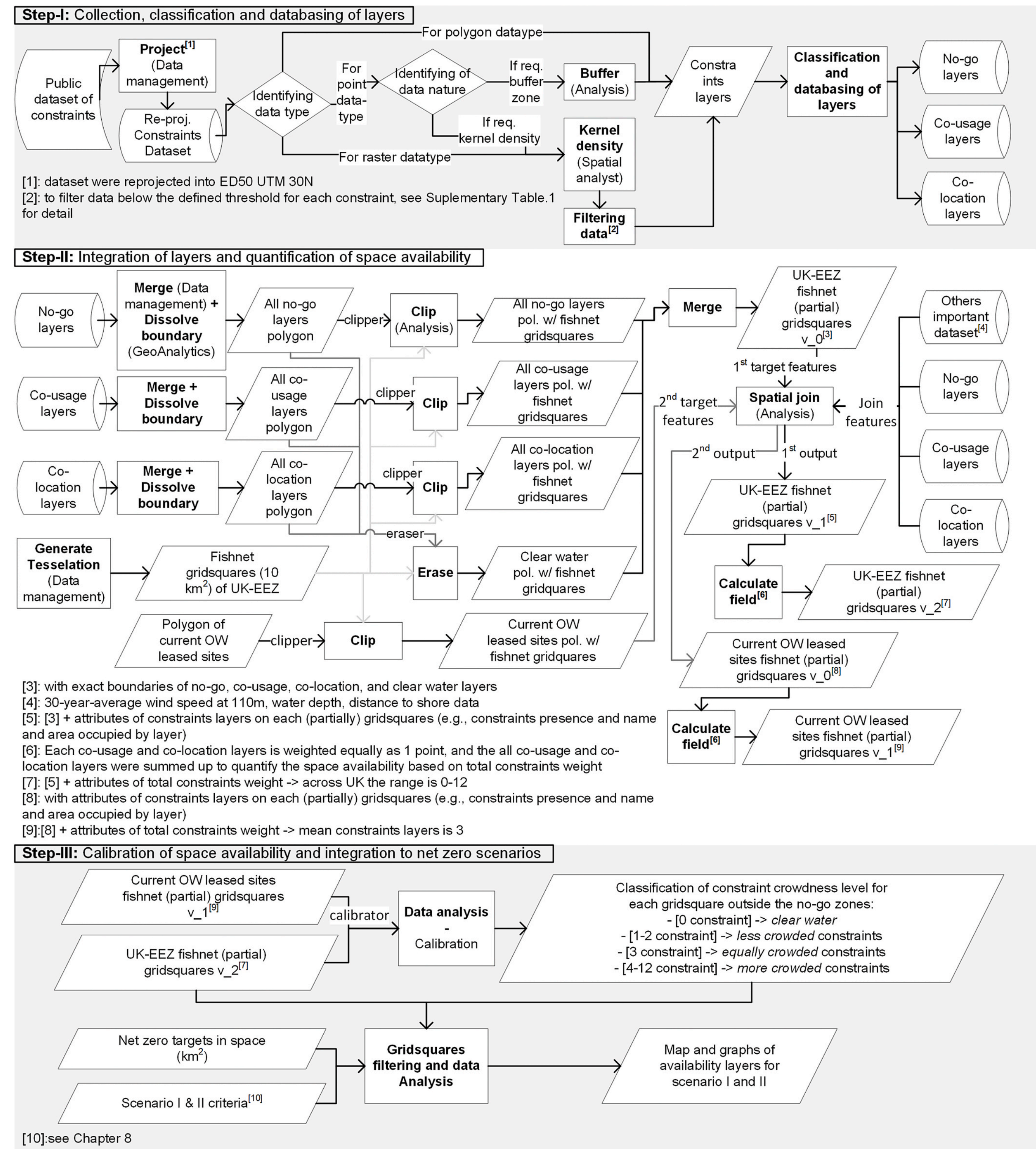


Fig. 3. Flowchart of spatial analysis conducted in this paper.

example, point data (such as protected wreck sites) were converted by applying a buffer distance to the point in order to generate a polygon. In other instances, simplistic buffering was not appropriate. For example, data for occurrence of threatened species as per the Oslo and Paris Convention (OSPAR) merely shows the points where species were observed, not their distribution [29]. In circumstances such as this, kernel densities were generated from the point data to create a surface from which polygons could be extracted [30]. All such processes applied to the raw data are shown in Supplementary Table 2 in Appendix A.2. The processing steps are described in the flowchart given in Fig. 3. These steps were carried out using ArcGIS Pro 2.7 but other GIS software with similar geoprocessing tools (e.g., ArcGIS Desktop/QRIS) can also be used to complete the GIS processing steps.

Table 1
Details of spatial feature layers (See Supplementary Table. 2 in Appendix A.2 for further details).

Feature type categorisation	Constraint function	Availability categorisation	Feature layer name (and short identifier)
Met-Ocean	To delineate areas with adequate wind resources	–	Wind speed, $\bar{v}_{110m}$ (at 110 m height)
Anthropogenic	To delineate areas that are occupied by other ocean economical activities	*No-go*	Active well sites (AcW) Aggregates sites (Ag) Aquaculture sites (Aq) Cables (C) Dredging sites (Dr) Harbour Areas & Facilities (HbA) IMO routes (IMOR) Mineral mining sites (MM) Ministry of Defence sites (Mlt) Non-Renewable Energy sites (NRn): (Oil and gas fields ceased after 2050 & infrastructures/ pipelines (OnGca2050)) Renewable energy sites (Rn) Vessel routes (VR) Waste disposal sites (WD)
	To delineate areas with protected heritage assets		Protected wrecks (PW)
	To delineate areas that are occupied by other ocean economical activities	*Co-usage*	Anchorage Areas (An) Carbon capture storage (CCS) Fishing sites (Fi) Non-Renewable Energy (NRn): (Oil and gas fields ceased before 2050 (OnGcb2050)) Site of specific scientific interest (SSSI)
		Co-location	Area of Natural Beauty (NaB) Heritage Coastline (HrC) Navigational Points (Nav) NATS – high radar interference (Ra) Seabed obstructions (SbO) Suspended well sites (SuW)
Geological			Geomorphology features (GmF) Steep slope zone (Slp) Submerged Landscape (SL)
Ecological	To delineate areas with high biodiversity/ designated for nature protection		Deep Sea Reservation (DSR) Fishing spawning & nursery ground for selected fish (FNS) Marine conservation zone (MCZ) OSPAR threatened species (OST) Special areas of conservation (SAC) Special protection area (SPA)

Table 2
Scenarios of installed OW power capacity by 2050 adapted from recent reports.

Demand Scenario	Sub-scenario	Power capacity, P target from OW by 2050, P_{2050} (GW)
Scenario A*: OW supplies domestic UK electricity generation demand	Headwinds (Electricity Generation)	65
	Balanced Net Zero Pathway (Electricity Generation)	95
	Widespread Engagement (Electricity Generation)	100
	Tailwinds (Electricity Generation)	125
	Widespread Innovation (Electricity Generation)	140
Scenario B**: OW supplies domestic UK electricity generation + green hydrogen demand	Headwinds (Electricity Generation + Green Hydrogen)	110
	Balanced Net Zero Pathway (Electricity Generation + Green Hydrogen)	154
	Widespread Engagement (Electricity Generation + Green Hydrogen)	157
	Tailwinds (Electricity Generation + Green Hydrogen)	203
	Widespread Innovation (Electricity Generation + Green Hydrogen)	226
Scenario C***: OW supplies domestic UK electricity generation + green hydrogen + energy export demand	Headwinds (Electricity Generation + Green Hydrogen + energy export)	350
	Balanced Net Zero Pathway (Electricity Generation + Green Hydrogen + energy export)	394
	Widespread Engagement (Electricity Generation + Green Hydrogen + energy export)	397
	Tailwinds (Electricity Generation + Green Hydrogen + energy export)	443
	Widespread Innovation (Electricity Generation + Green Hydrogen + energy export)	466

* Sub-scenarios in this theme and P targets were based on the sixth carbon budget report by [25].

** Sub-scenarios in this theme and P targets were based on the sum up of P targets on the first theme for electricity generation and the max demand of P of green hydrogen production with OW as the energy supplier. The max P of green hydrogen is measured from the required annual demand of hydrogen production in the sixth carbon budget report by [25,31]. The required annual hydrogen production was converted to a required power by divided the annual hydrogen production by the typical capacity factor of OW (using 40% [32]).

*** Sub-scenarios in this theme and P targets were based on the sum up of the second theme with 240 GW as the number that could be exploited to achieve the beneficial export value of energy export abroad in the OW and hydrogen integrated system as stated in the report by [26].

2.2. Feature and availability categorisation of layers

Four feature categories were created to group and describe the input layers: (i) metocean, (ii) anthropogenic, (iii) geological, or (iv) ecological. Each polygon constraint layer was ascribed to its appropriate feature category to aid aggregation. Afterwards, all categorised layers of the same value were merged to create the met-ocean, ecology, geology, and anthropogenic layers discussed in section four.

To create the availability layers, each polygon constraint layer was given an availability value: either (i) *no-go*, (ii) *co-usage*, or (iii) *co-*

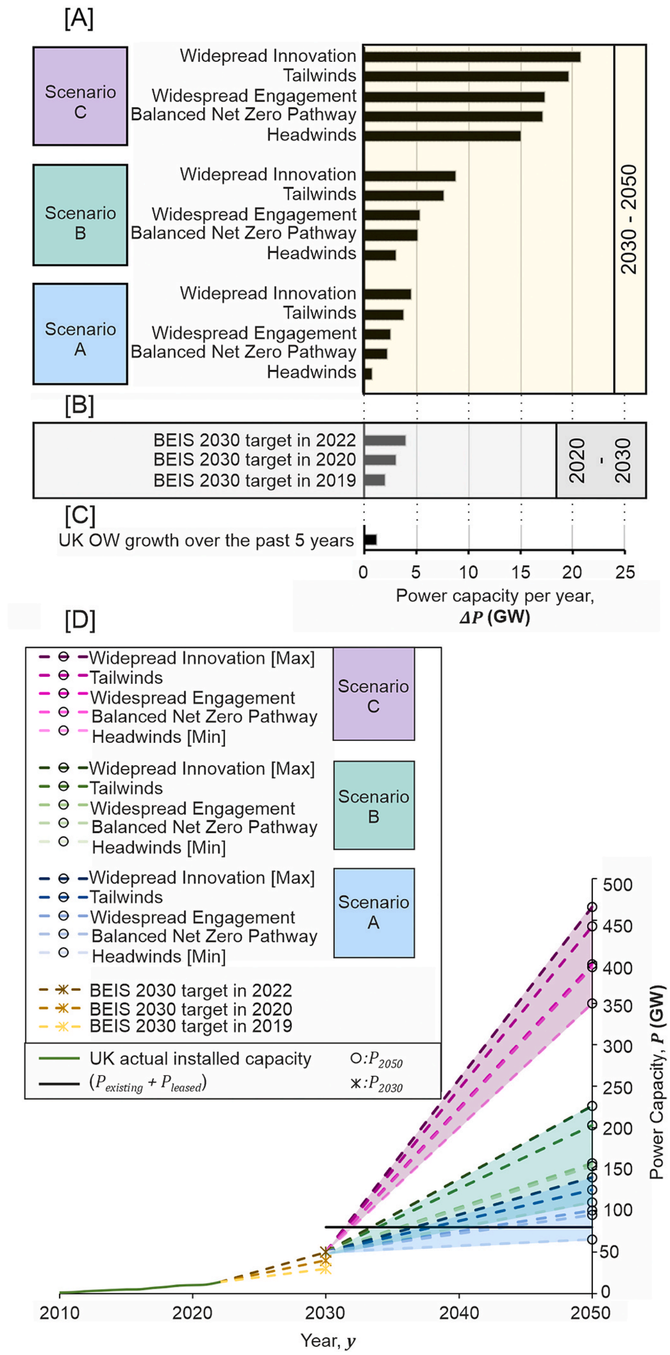


Fig. 4. Growth of OW power capacity needed from different scenarios: [A] Linear growth of extra OW power capacity needed per year, (ΔP) from 2030 to 2050 for different net zero scenarios, [B] Linear growth of ΔP from 2020 to 2030 for different BEIS 2030 targets, [C] UK ΔP growth over the past 5 years, and [D] Estimation of annual P increment and future targets, P_{2030} and P_{2050}, and $P_{existing} + P_{leased}$.

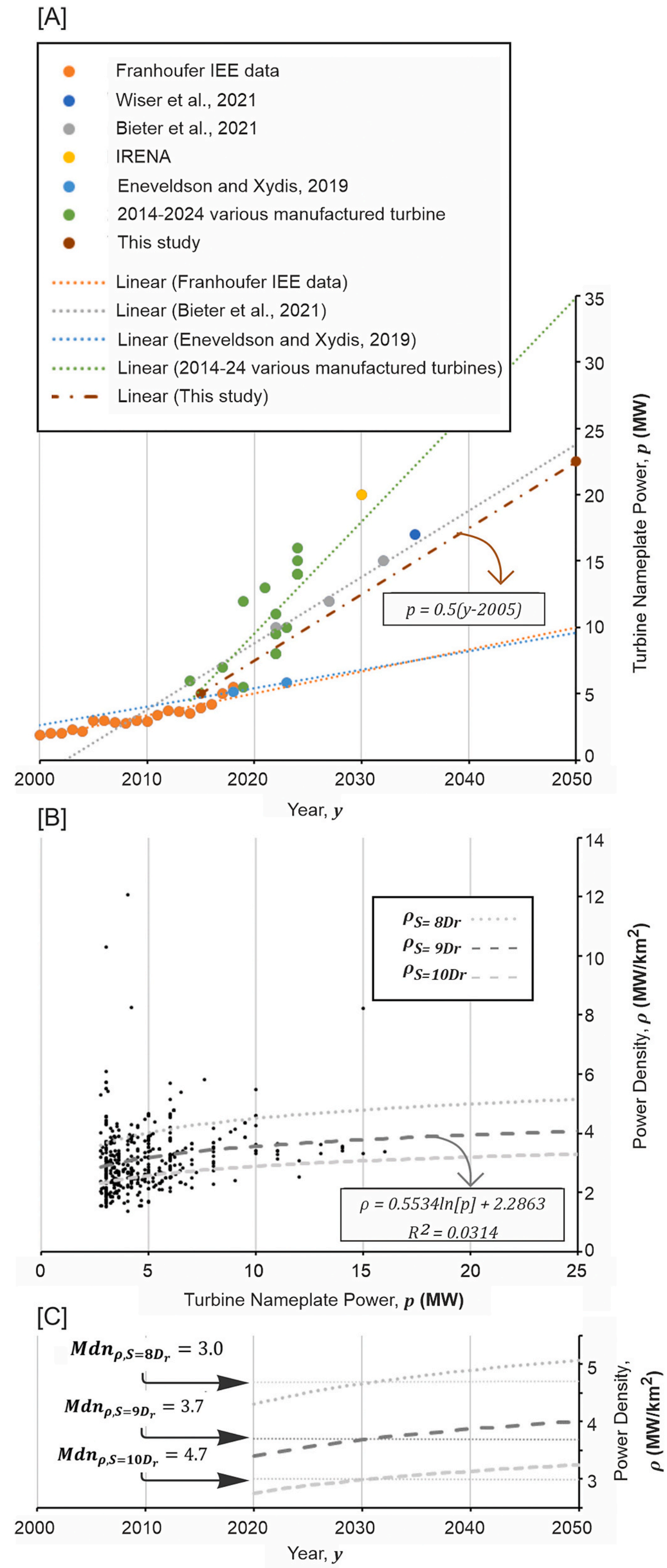


Fig. 5. Estimation of power density, ρ progression: [A] Estimation of turbine nameplate power, p progression throughout year, [B] Estimation of ρ for a given turbine nameplate power, and [C] Estimation of ρ progression throughout year. See Supplementary Table. 3 for the details of the collected datasets.

location (see Table .1). These availability categories are defined as follows:

- *A no-go* zone has layer(s) of anthropogenic constraints that could not co-exist with an OW site. The basis of the no-go categorisation is either a regulatory issue that restricts utilisation of the space for OW due to a specific use (e.g., mining, aggregate, or ministry of defence sites), a safety issue (e.g., vessel routes, IMO routes, or active well sites), or because of existing infrastructure at the site (e.g., existing

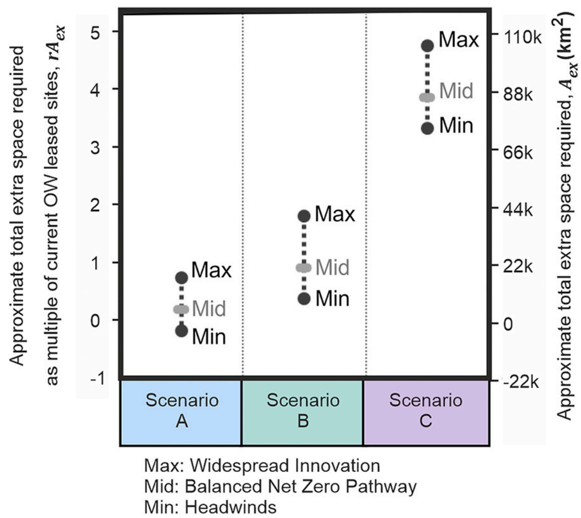


Fig. 6. Approximation of total extra space, A_{ex} required from different scenarios of net zero targets and the ratio to the current OW leased sites, rA_{ex}: [A] electricity generation only, [B] electricity generation + green hydrogen, and [C] electricity generation + green hydrogen + energy export.

renewable energy sites, cables, or active oil and gas infrastructure or pipelines).

- *A co-usage* zone has one or more layers of anthropogenic constraints that involve direct human activities that require usage of the space that could co-exist with OW (e.g., inshore fishing, oil and gas sites that would cease before 2050, or carbon capture storage sites), although adjustment that would restrict or constrain one or both activities may be needed.
- *A co-location* zone has one or more layers of (i) anthropogenic constraints that do not involve direct human activities in that space but form some other constraint (e.g., areas of natural beauty, or heritage coastline), (ii) obstructions in the atmosphere, sea or seabed due to anthropogenic activities (e.g., suspended wells, radar interference, or navigation points) and/or (iii) non-anthropogenic constraints (e.g., geomorphological features, or special protected areas) that could co-exist together with OW, although allowance or adjustments such as turbine micrositing or mitigation measures may be required.

The zones for each availability were combined to create *no-go*, *co-usage*, and *co-location* layers, with the remaining space defined as the *clear water* layer, where no constraint features are present.

This categorisation process led to a zoning of the UK-EEZ into sea regions that are *no-go* areas, *clear water* (i.e., *go* areas, meaning no constraints), and then areas that have an intermediate availability, due to *co-usage* and *co-location* constraints. This intermediate availability level was quantified using a layer mask, described in the next subsection.

2.3. Availability level – the quantitative layer mask

To create this quantitative layer mask a fishnet of 10 km^2 grid squares that covered the UK-EEZ was generated. Each grid square was then classified based on the presence of the three zone values: (i) *no-go*, (ii) *clear water* and (iii) areas with *co-usage* and/or *co-location*. This

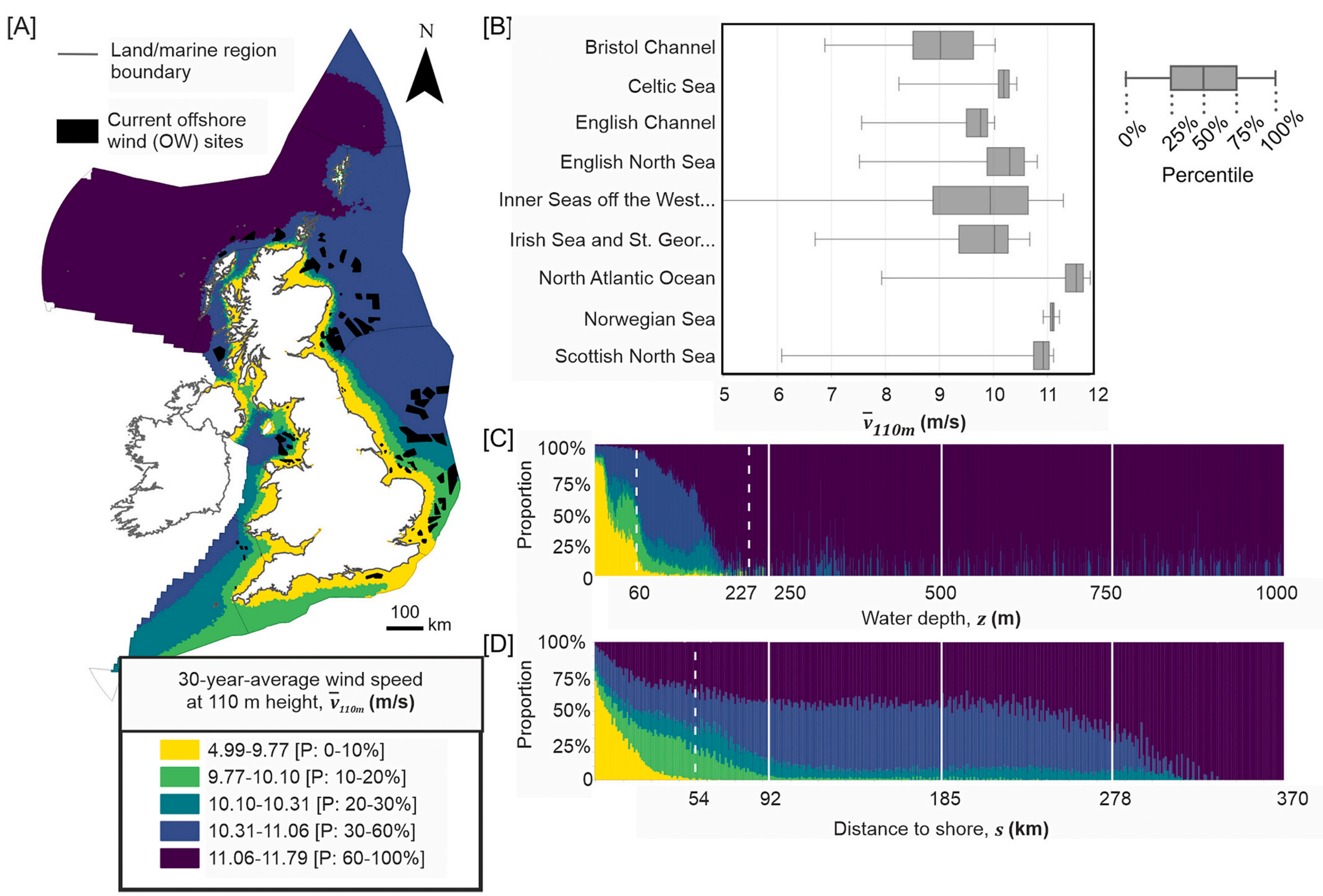


Fig. 7. Met-ocean/30 -year-average wind speed, $\bar{v}_{110m}$ layer in UK-EEZ waters: [A] in map, [B] in box plot, [C] & [D] $\bar{v}_{110m}$ classes varying with water depth and distance to shore respectively.

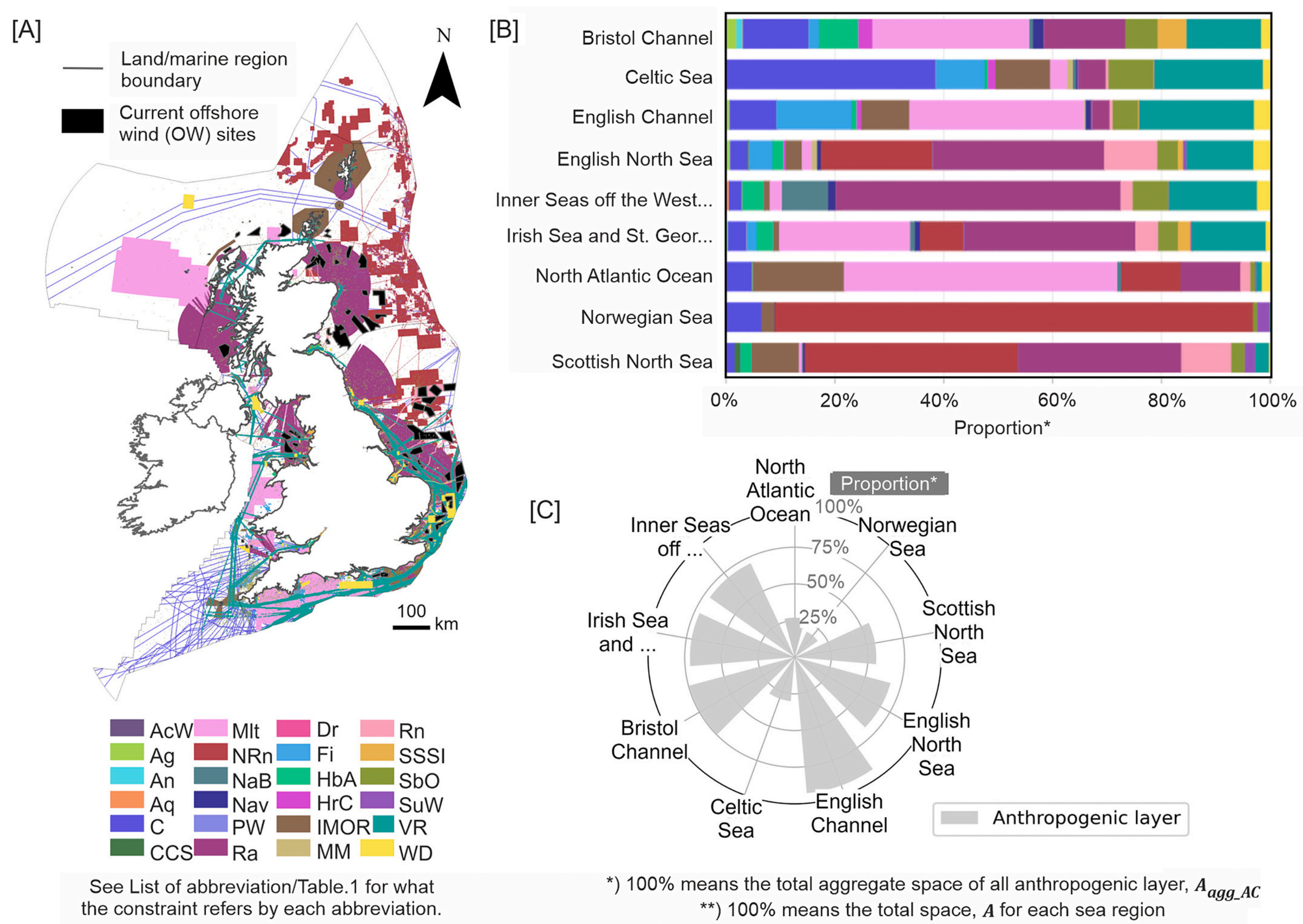


Fig. 8. Anthropogenic layers in UK-EEZ waters: [A] in map, [B] in stacked bar chart, and [C] in radar plot.

process divided some grid squares into slivers with each of the three values.

For each whole or partial grid square in the *co-usage* and/or *co-location* zones, the total number of *co-usage* and/or *co-location* layers are summed to define availability. Some prior studies (e.g., [16,19,21]) have assigned a different weighting to each layer, but in this case each layer has equal weight, apart from the specific *no-go* weighting which eliminates that area from the analysis. The resulting quantitative layer mask ranges from 0, for *clear water* zones, through the range 1–12 with 12 being the maximum number of co-usages and co-locations at any location. *No-go* areas are marked as null. The steps to create this quantitative layer mask are given in more detail in Step-II of Fig. 3.

In Section 6 we discuss a calibration exercise that uses this quantitative layer mask to identify the levels of *co-usage* and *co-location* at current OW leased sites. In section 7 & 8 the calibrated version of this quantitative layer mask is described and integrated with net zero targets and further site criteria to discuss insights into future OW plans in UK.

2.4. Limitations

There are a number of limitations inherent within the approach adopted by this study that need to be made clear.

- Input data vary in quality (resolution, precision, accuracy) and time depth (current voracity, potential for variability over time). For example, geological mapping is based on geophysical and geotechnical data of variable density, with some areas reliant on greater levels of interpolation than others. The outcome is varying degrees of confidence in the interpretation for any given grid square.
- The overlaying of net zero targets to the space availability map is based on the projection of energy density by 2050 drawn from publicly available datasets and is liable to change.
- This study measures crowdedness of constraints in a simple additive manner. This overlooks the possible complexity of interaction between constraint types. For example, two particular constraints might interact in such a way to render any further use of space unlikely.
- The list of variables used as constraints are derived from previous studies, current consenting requirements, and accessibility to those datasets in the UK waters (see the selection process in Appendix A.1). For example, no attempt has been made to incorporate intangible heritage despite its importance due to lack of available data.
- Many datasets represent a snapshot of the current state of knowledge, rather than the broader potential for a constraint to be present. For example, the location of wrecks relates to those currently known by the UKHO. New wrecks will continue to come to light as further surveys are carried out and are more likely to happen in some areas than others. We have not attempted any predictive modelling to account for this likelihood.

Future studies may adapt this method for other regions to address space availability for future OW based on crowdedness of constraints and then overlay their net zero targets on it. This would also allow for regional differences in legislation and data quality to be accounted for.

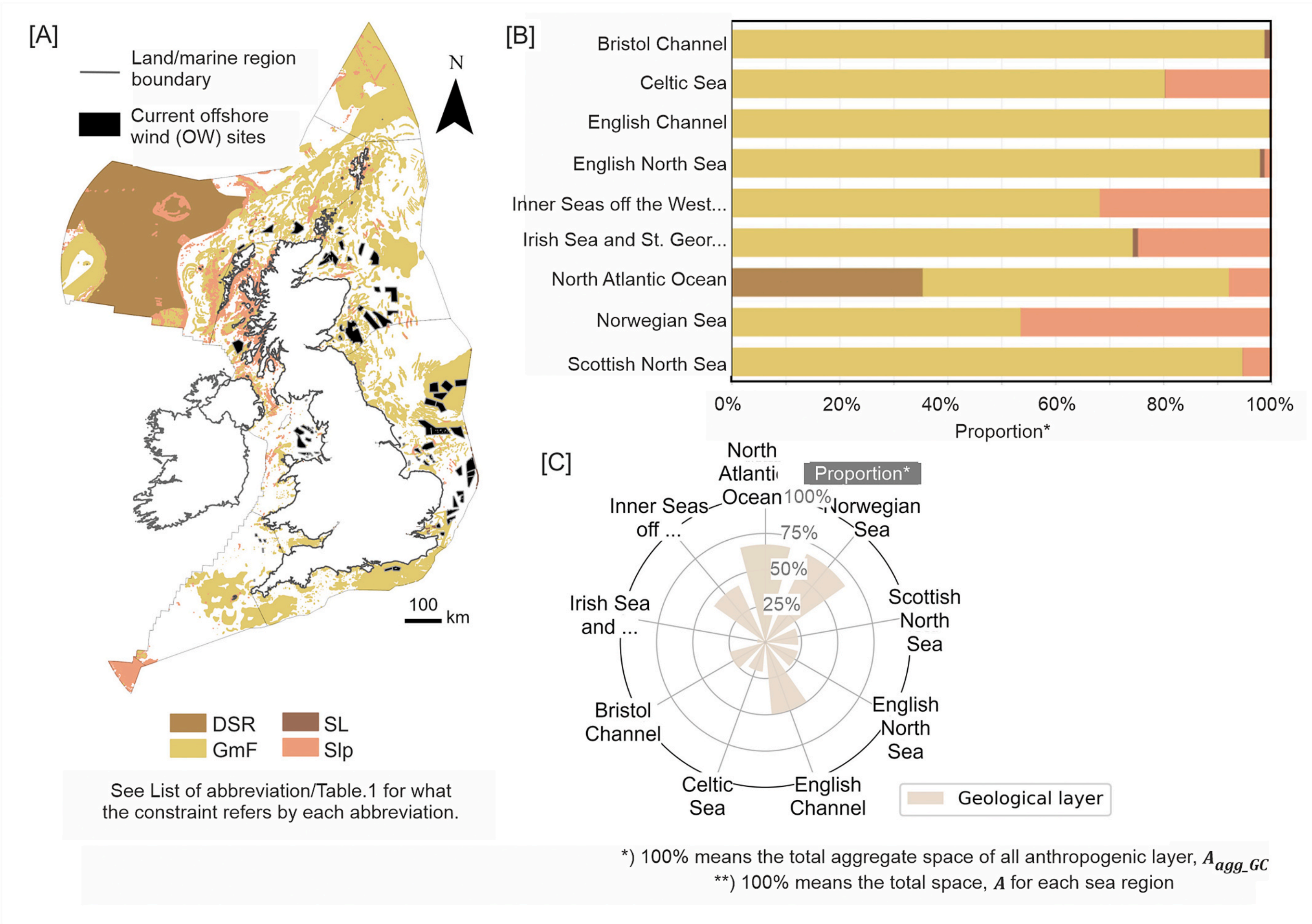


Fig. 9. Geological layers in UK-EEZ waters: [A] in map, [B] in stacked bar chart, and [C] in radar plot.

3. Required space for future offshore wind

To determine the total extra space required for future OW in the UK-EEZ waters, *Aex* we first identified the different OW capacities that are projected to meet the UK's net zero targets for 2050, as well as other projections of future UK OW growth. These capacity predictions are converted into space requirements based on likely future turbine characteristics. This analysis is elaborated in the following subsections.

3.1. Different scenarios of offshore wind by 2050

Three different broad scenarios can be drawn from recent studies [25,26] on how OW power will support UK and global net zero targets by 2050. The first scenario, A is based on a low ambition target where OW will meet domestic UK electricity generation requirements for surface transport, buildings, manufacturing & construction, fuel supply, and other sectors as set out in the 2020 Sixth Carbon Budget [25,31]. This scenario requires 65–140 GW of OW capacity (see Table .2 for details).

The second scenario, B involves OW supplying both domestic electricity generation and green hydrogen production for domestic UK use as the economy is decarbonised. The power capacity for various sub-scenarios of this kind in this theme was totalled from the demands for electricity generation and green hydrogen production. The range of sub-scenarios are given in Table .2, drawn from the range of energy production requirements given in the Sixth Carbon Budget [25]. The resulting capacity range for this second scenario is 110–226 GW (see Table .2 for detail).

The last scenario, C involves the most ambitious OW growth, to support electricity generation and green hydrogen production for the UK domestic needs as well as to meet energy export demand. This scenario adds a further 240 GW of capacity for energy export [26], which identifies this value as potential OW capacity to supply a projected deficit in zero-carbon hydrogen in mainland Europe and which would create a significant economic impact with an annual export value of up to £48 billion. The resulting OW capacity for this third scenario is in the range from 350 to 466 GW (see Table .2 for detail).

In the shorter term, the UK has maintained a target of installed OW capacity by 2030 as part of successive government strategies. This target for 2030 has evolved from 30 GW in 2019 [33] to 40 GW in 2020 [34] and most recently 50 GW in 2022 [6]. These targets reflect evolving net zero plans and industrial strategies, and the most recent adjustment was also influenced by elevated energy security concerns from the Russian invasion of Ukraine [6,25].

The 2030 target provides a useful benchmark to give an average growth rate needed for each scenario from 2030 to 2050 (Fig. 4a). Over the past 5 years (2017–2021) the UK OW operational capacity has increased by 1.2 GW/year [35] (Fig. 4c). In contrast, to meet the most recent 2030 target of 50 GW requires a growth rate of 4 GW/year (Fig. 4b). For 2030–2050, the future scenarios involving OW-sourced green hydrogen typically involve growth rates of 5 GW/year or more, and the energy export scenarios involve 15 GW/year or more.

The current OW leased sites in the UK (England, Wales, Northern Ireland, and Scotland) including projects that are in operation represent $P_{existing} = 11GW$ while those in construction, committed and under development/pre-planning could amount to $P_{leased} \sim 69\ GW$ [36] if all

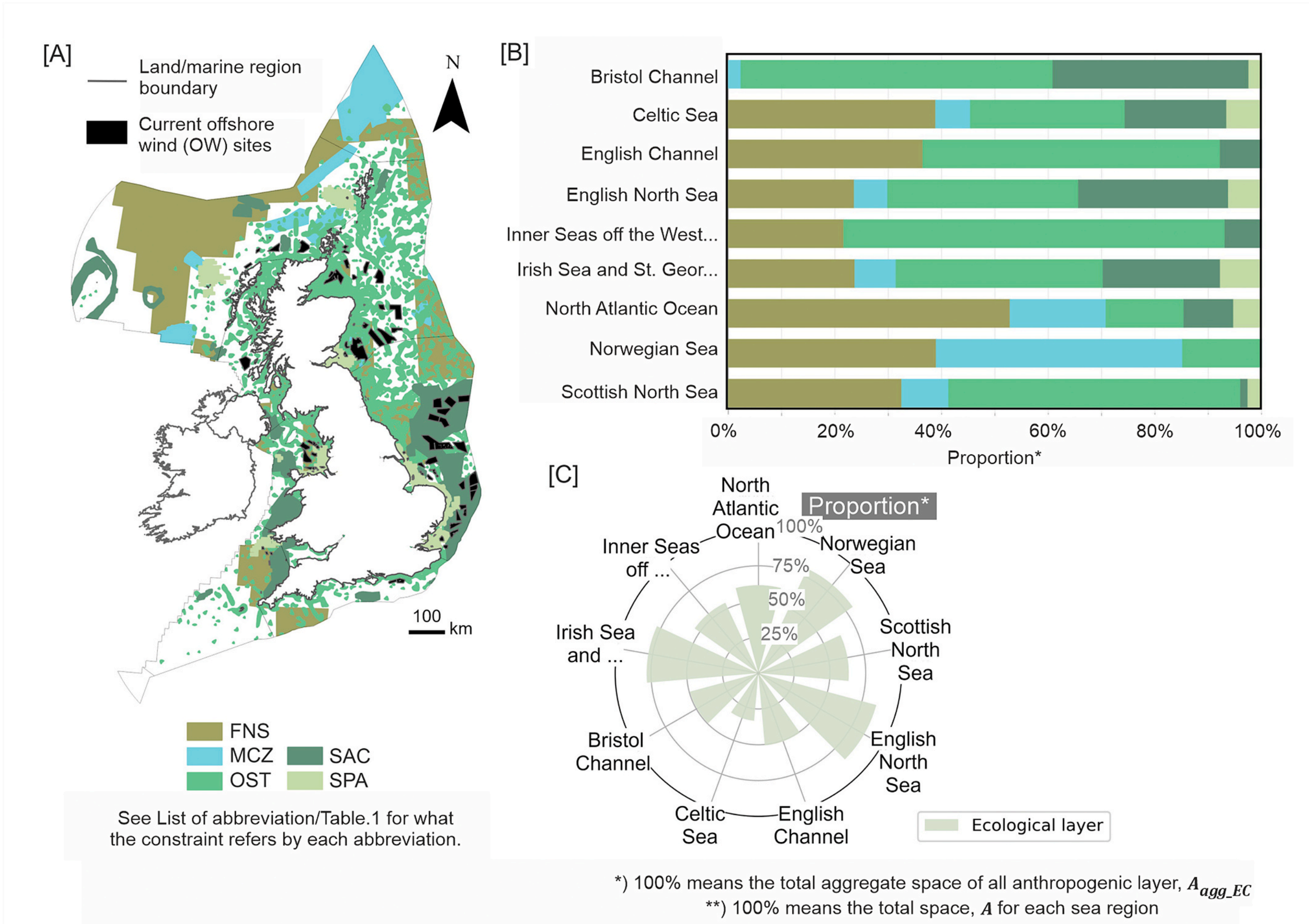


Fig. 10. Ecological layers in UK-EEZ waters: [A] in map, [B] in stacked bar chart, and [C] in radar plot.

enter production. Therefore, it can be assumed that additional ocean space is only needed for installed capacity above 80 GW, although this overlooks the possibility of some leased sites not completing the development consenting process, which has precedent [37].

3.2. Conversion of power capacity to space demand

To convert the installed capacity targets into space requirements, a power density – i.e., installed power per unit plan area of ocean space – was derived based on future turbine characteristics. The evolution of turbine capacity was estimated based on collated datasets (see Supplementary Table 3 in Appendix A.2), which lead to linear regression lines associated with past and future trends (Fig. 5a). A linear regression through 2014–2024 data of various manufactured turbines indicates the highest future trend, while the linear regression line from Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (IEE) data and from [38] shows a lower trend. From those most optimistic and pessimistic lines, a middle line was adopted as the predicted future capacity.

The turbine nameplate power, p is then converted to power density, ρ, taking into account the rotor diameter, D_r and the minimum turbine spacing, S, assuming a rectangular grid:

$$\rho = \frac{p}{(SD_r)^2} \tag{1}$$

The published turbine dataset includes a range of ratios $p/\ (D_r)^2$ which leads to the scattered power density data shown in Fig. 5a. This shows that the power density is only weakly dependent on the turbine size. Logarithmic regression lines are shown for typical spacings in the range from $S = 8 - 10$ [39,40]. The analysis in this paper is based on the asymptote of the $S = 9$ regression line which is $\rho \sim 4.0$ MW/km^2 (Fig. 5b). This is consistent with the power density from the current OW leased sites and an earlier study [9], which is ~3.6 MW/km^2.

The linear prediction of nameplate capacity and the regression line of power density give the power density progression from 2020 to 2050 (Fig. 5c). By combining that with the linear growth model to 2050 (Fig. 4), the additional ocean space for each scenario is found, and expressed in both km^2 and as a multiple of current leases in Fig. 6. For the scenarios including green hydrogen (scenario B–C), the required additional UK ocean space ranges from 8000 to 105,000 km^2 by 2050.

4. Feature categorisation layers

In this section, the 34 feature layers of the spatial model are introduced by category, with key aspects of their source, processing and categorisation explained. Each section includes discussion of critical elements that emerged from the analysis.

4.1. Met-ocean feature layer

The first layer category is met-ocean and comprises a single layer – the 30-year-average wind speed at 110 m hub height, $\overline{v}_{110m}$ (Fig. 7). This shows that the whole offshore UK-EEZ has a $\overline{v}_{110m} > 5.0$ m/s. The whole UK-EEZ has an average wind speed in the feasible working range for wind turbines (4–25 m/s) [10], even in sheltered sea regions close to

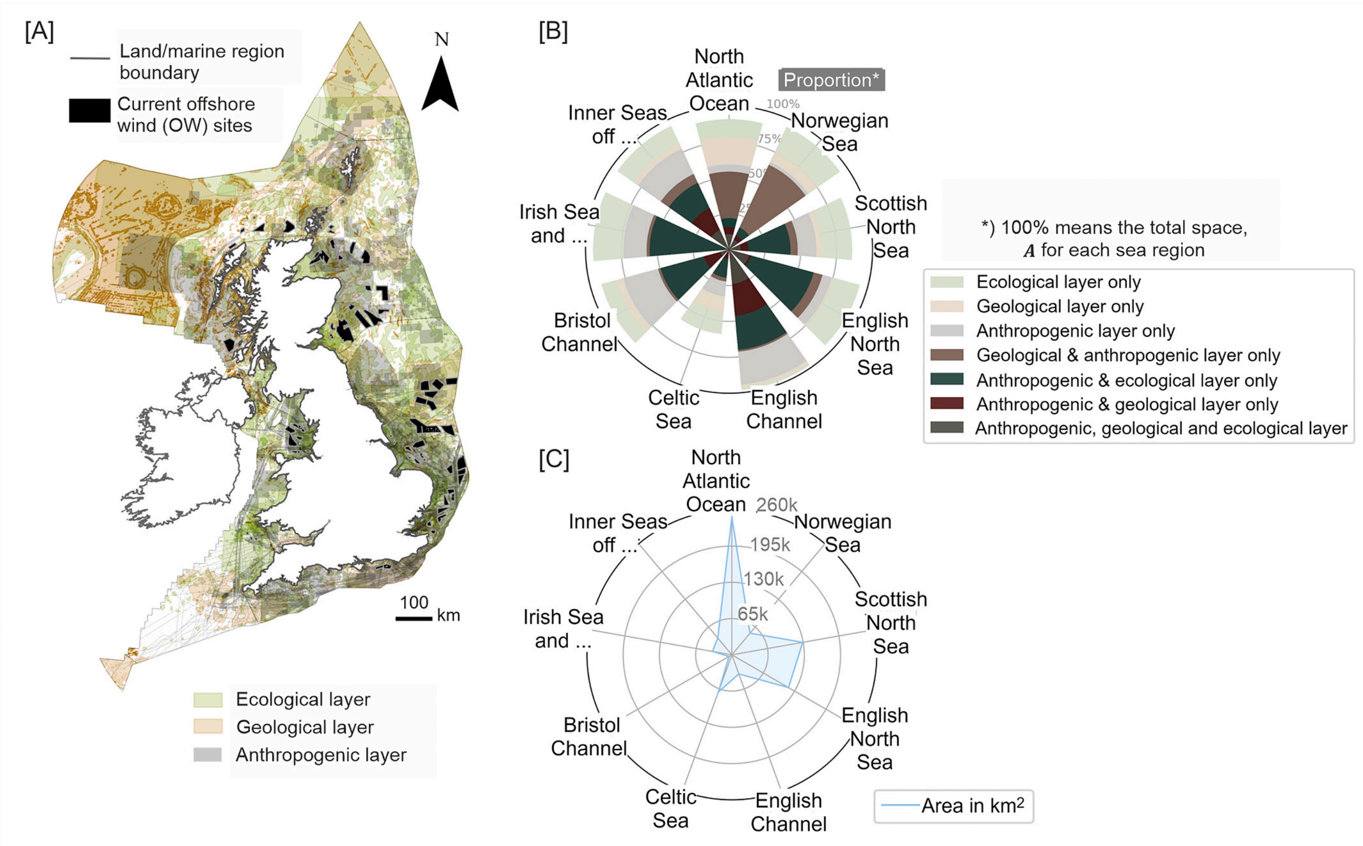


Fig. 11. Integrated anthropogenic, geological, and ecological layers in UK-EEZ waters: [A] in map and [B] in radar plot, while [C] show the total area in each sea region.

land such as the Bristol Channel.

The northern sea regions (i.e., North Atlantic Ocean and Norwegian Sea) have higher $\bar{v}_{110m}$, while lower $\bar{v}_{110m}$ are found in shallower waters and closer to shore (see Fig. 7c/7 d for the whole UK waters or use Dashboard [1][3] to examine each sea region). Many early UK OW farms are in lower $\bar{v}_{110m}$ areas, close to shore and in shallow water, for example in the southern part of the English North Sea. More recent leases are in regions with 10–11 m/s of $\bar{v}_{110m}$, and the latest ScotWind round includes leases in regions of 11–12 m/s of $\bar{v}_{110m}$ off the northwest coast of Scotland.

4.2. Anthropogenic feature layers

Anthropogenic feature layers cover 46% of the UK-EEZ, including parts of all sea regions (Fig. 7). The 24 types of anthropogenic feature are listed in Table 1, which also shows the short identifiers used in the legend of Fig. 8a. The layers are stacked alphabetically, so the visual appearance of Fig. 8a does not indicate the relative sizes of each feature, which is instead portrayed in Fig. 8c. The proportional coverage of each sea region is shown in Fig. 8b. The English Channel, Bristol Channel, and the Irish Sea and St. George's Channel are the three most crowded sea regions by anthropogenic features, with 70–90% coverage. The Celtic Sea, North Atlantic Ocean and Norwegian Sea are the least crowded with only 20–30% coverage.

Each marine region has a different mixture of anthropogenic feature layers, as depicted by the stacked bars in Fig. 8b. These show the distribution by area of anthropogenic feature, irrespective of whether features have overlap. In some regions such as the English Channel, North Atlantic Ocean, and Bristol Channel, the dominant anthropogenic layer is Ministry of Defence sites (Mlt). In the Inner Seas off the West Coast of Scotland and the English North Sea, High-interference Radar Zones (Ra) dominate. In the Scottish North Sea and Norwegian Sea, Non-Renewable energy sites (NRn) linked to the oil and gas industry dominate, while in the Celtic Sea, the main anthropogenic constraint is Cables (C), which are primarily linked to transatlantic communication.

4.3. Geological feature layers

Geological feature layers cover 59% of the seafloor in the UK-EEZ, as listed in Table .1 and shown in Fig. 9 using the same format and subfigures as Fig. 8. The regions most occupied by geological features are the Norwegian Sea, the North Atlantic Ocean, and the English Channel with ~50–70% coverage. Other regions, except the Inner Seas off the West Coast of Scotland (with ~37% coverage), have <25% of coverage by geological feature layers (Fig. 9b).

Each region also has its own geological feature layer characteristics (Fig. 9c), and every region has significant areas covered by Geomorphological Features (GmF) layer. These represent seabed with rocky outcrops or hard substrates, submerged channels or tunnel valleys, pockmarks, or sediment waves, that can present a geohazard to the design and installation of OW.

4.4. Ecological feature layers

63% of the UK-EEZ waters have one or more ecological features as listed in Table 1 and shown in Fig. 10. The English North Sea, the Norwegian Sea, and the Irish Sea and St. George's Channel have the highest coverage, exceeding 75%. All other regions are at least 50% occupied by ecological features, except for the Celtic Sea, which has

[3] See Appendix A.3

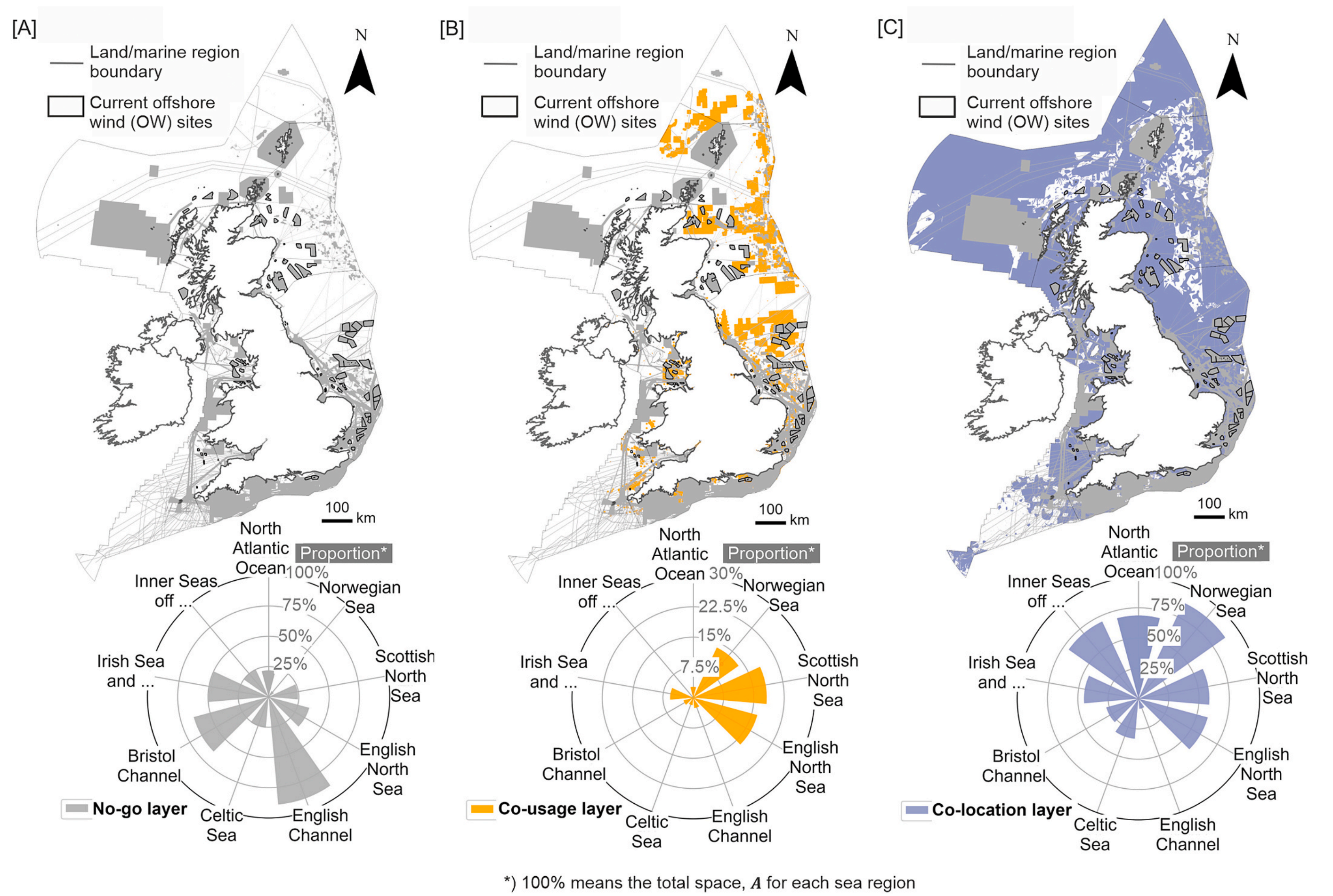


Fig. 12. *No-go* [A], *co-usage* [B], and *co-location* [C] layers in UK-EEZ waters.

<30% coverage (Fig. 10b).

Most of the ecological feature layer coverage in the Bristol Channel, the English Channel, the Inner Seas off the West Coast of Scotland, and the Scottish North Sea is the layer of OSPAR threatened species (OST). In the Celtic Sea and the North Atlantic Ocean, the most significant coverage is from nursery and spawning grounds for fisheries (FNS). The Norwegian Sea is dominated by Marine Conservation Zones (MCZ) (Fig. 10c).

4.5. Combined feature layers

In Fig. 11, all anthropogenic, geological, and ecological layers are combined with colour-coding that shows how anthropogenic, geological, and ecological constraints often coincide. There is at least one feature layer over >80% of every sea region, except for the Celtic Sea, which is significantly less constrained with <60% coverage by one or more feature layers. There is more than one feature layer in over 65% of the Norwegian Sea and the English North Sea and 55% of the English Channel.

5. Availability categorisation layers and availability level

The combined feature layers, with their availability classifications (Table 1), have been used to create categorised maps of availability (Fig. 12).

5.1. No-go layer

The *no-go* zones are depicted in Fig. 12a, which highlights the existing congestion in the English Channel, where ~80% of the region is a *no-go* zone. The Bristol Channel, the Irish Sea and St. George's Channel, and the English North Sea are also relatively congested, being ~65%, ~50%, and ~30% *no-go* respectively. The Norwegian Sea is the least constrained with <5% no-go zones.

5.2. Co-usage layer

The *co-usage* zones, where there is potential for OW sites to be co-located with current anthropogenic activities or features, do not exceed 20% in any single sea region (Fig. 12b). The English and Scottish North Sea are 17–20% available for *co-usage* whereas in the Celtic Sea and the North Atlantic Ocean the *co-usage* zones are <4%.

5.3. Co-location layer

Co-location zones, where OW sites could co-exist with constraints as listed in Table .1, are found in all sea regions (Fig. 12c). *Co-location* zones cover >50% of each region except for the Irish Sea and St. George's Channel, Bristol Channel, Celtic Sea, and English Channel. The highest coverage by co-location is the Norwegian Sea at ~85%. The lowest outlier is the English Channel with only <5% coverage followed by Bristol Channel and Celtic Sea with <30% coverage.

5.4. Quantitative availability map

The previous analysis leads to a quantitative availability map (Fig. 13), with the sea area categorised by the number of constraint layers present (whether *co-usage* or *co-location*), on a scale from zero

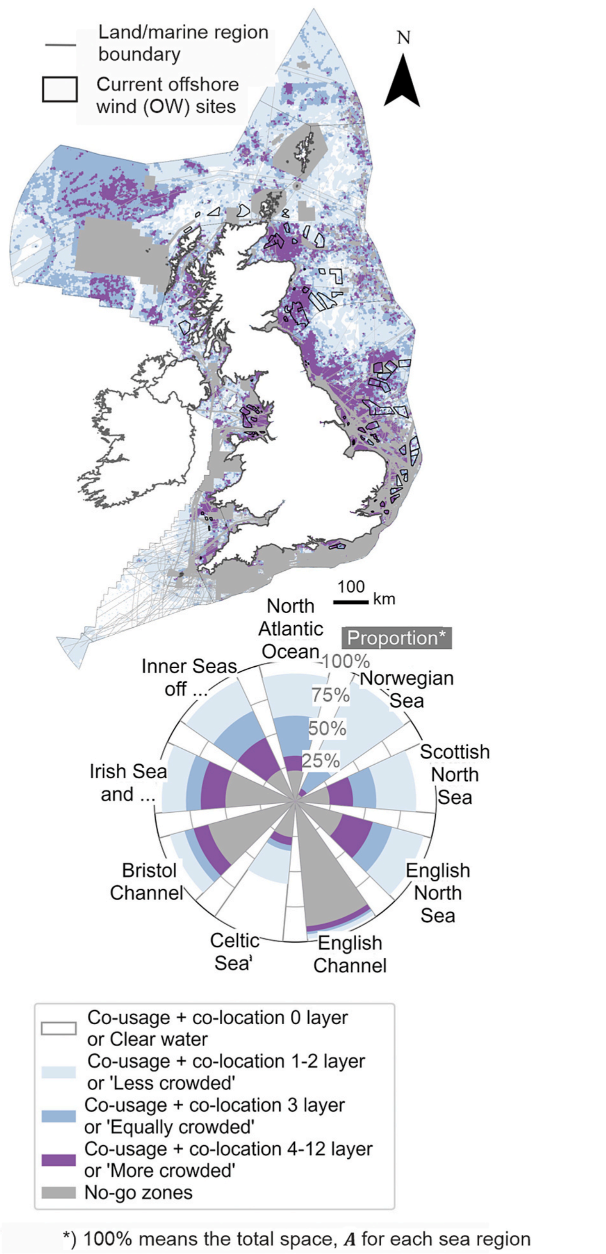


Fig. 13. Quantitative availability level in UK-EEZ waters.

(referred to as *clear water*) to 12 (the maximum number of feature layers that overlap anywhere). A further null categorisation applies to *no-go* areas, which are classified as unavailable for OW. This information is available supplementary data through Dashboard [2][4].

When viewed by sea region, the outliers are the Celtic Sea and the English Channel, which have relatively high and low availability respectively. The Celtic Sea is >40% *clear water*, in contrast to the other sea regions for which the *clear water* zone occupies <20%. The English Channel is >80% *no-go* space, whereas most other sea regions have 25–50% *no-go* space.

Between the *clear water* and *no-go* space is a range of constraint levels, divided into three categories according to the number of feature layers, as described in Section 6).

[4] See Appendix A.3

6. Constraints at current OW leased sites

An enlarged version of the availability level map is reproduced in Fig. 14 with a focus on the areas of current OW leases. In this section, the availability level characteristics of these sites are explored, as a calibration of the level of co-usage and co-location that has been accepted at the current level of OW deployment. The resulting statistics of the availability level at current OW sites are subsequently used to define the rest of the UK-EEZ as *less crowded* (i.e., containing fewer *co-usage* and *co-location* layers than the median of current OW leases), *equally crowded* (i.e., containing equal layers) or *more crowded* (i.e., containing more layers). But firstly, the basic characteristics of the current OW sites are examined: water depth and distance to shore.

The current OW leased sites are classified throughout this analysis based on their status (i.e., leased rounds, demonstrators, or extensions from current sites), region (in England, Wales, and Northern Ireland or in Scotland) and the leasing round.

6.1. Water depth and distance to shore

The mean and ranges of water depth and distance to shore of each current OW leased site is shown in Fig. 15, using markers for each 10 km^2 grid square, and the resulting distributions also shown. Current OW leased sites are in water depth of up to 128 m. A depth of 60 m is used in this analysis as a boundary where fixed bottom foundations become less favourable than floating foundation [41]. Using this basis, ~70% of the current OW leases are in fixed-bottom locations. Most floating OW locations are from the recent (January 2022) ScotWind leasing round, of which 80% was in water depth >60 m (see Fig. 15a). Prior to this major leasing round, only <15% and 10% of pre-ScotWind sites and demonstrators were in water depth >60 m (see Fig. 15a). This contrast highlights the pre-dominance of fixed-bottom conditions in earlier rounds, and the rapid acceleration of deeper conditions that favour floating systems.

The current OW leased sites are up to 231 km from shore, although 50% of the leased area is <54 km from shore, and 90% is <137 km from shore (see Fig. 15a). The greater distances from shore are primarily from the recent ScotWind sites and TCE Round [4] (Fig. 15b). This transition shows the depletion of nearshore sites and highlights the emerging need for longer cabling and greater transit distances for operations and maintenance.

6.2. Availability level

The availability levels in the current OW leased sites are summarised in Fig. 15c. The number of *co-usage* and/or *co-location* constraints varies from 0 to 10 with a median of 3.90% of the space has 5 or less *co-usage* + *co-location* layers. On this basis, the remainder of the UK-EEZ has been assigned the following availability labels: *less crowded* for 1–2 layers, *equally crowded* for 3 layers, and *more crowded* for 4 or more layers. These availability characteristics are bounded by the *clear water* (for 0 layers), and *no-go* classifications described earlier.

The availability level for each classification of current OW lease is shown in Fig. 15c. The recent 2022 ScotWind round uses sea areas with the best availability, with 70% falling in *less crowded* space. The Crown Estate (TCE) Round [3] sites are 68% in areas of *less crowded* or *equally crowded* availability. In contrast, all areas of TCE Round [1] and fixed-bottom demonstrator sites are in areas of *more crowded* availability. This shows that leases are not progressively moving into *more crowded* waters. Instead, the move to deeper water, further from shore, brings new leases into *less crowded* sea areas.

7. Future OW sites: characteristics and constraints

The availability calibration derived in Section 6 is applied to the availability level mask to explore potential future OW sites across the

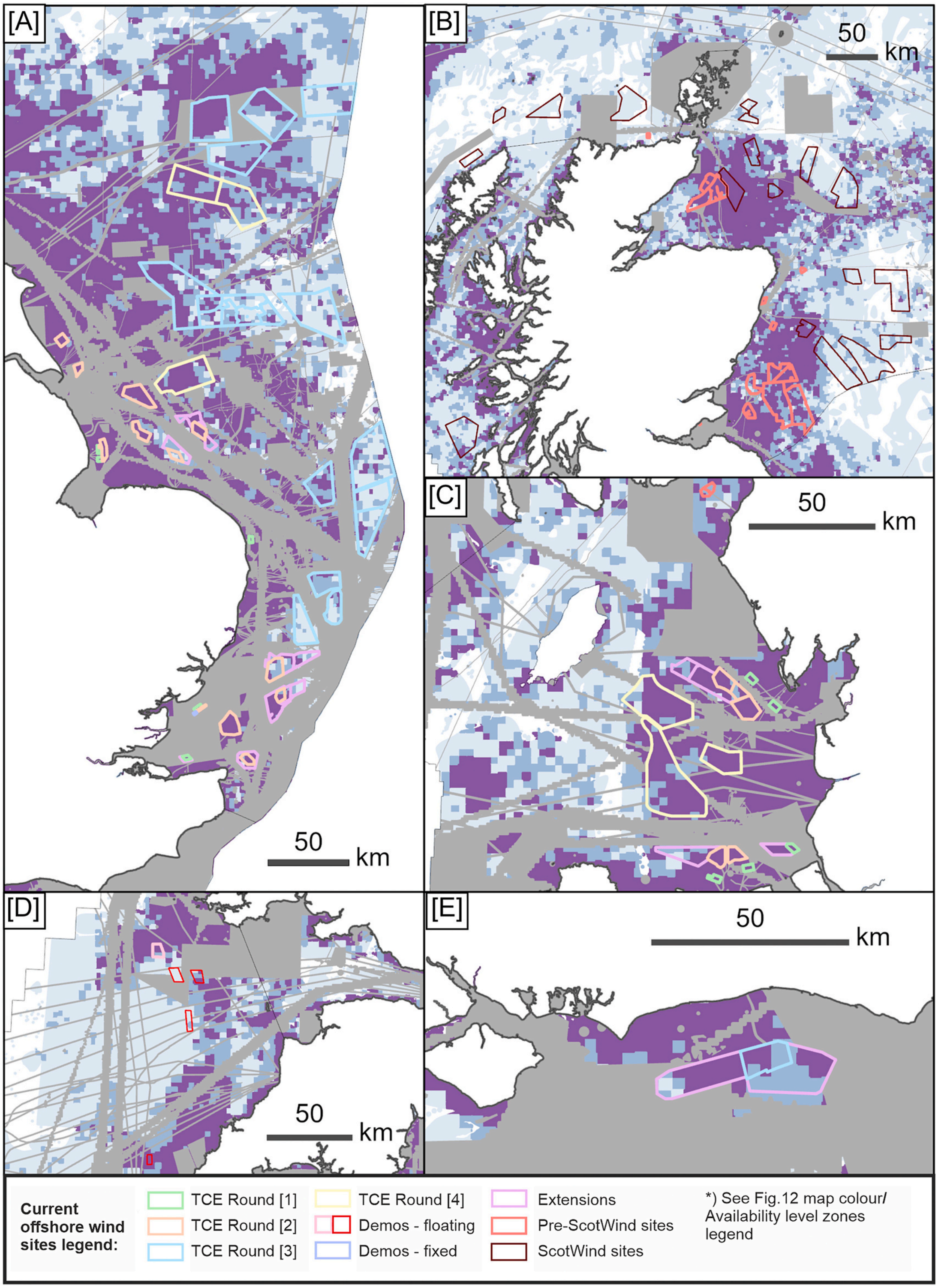


Fig. 14. Enlarged availability level map (Fig. 13) focused on current OW leases.

UK-EEZ. The range of water depth and distance to shore for each sea region is shown in Fig. 16. Only ~30% of the UK-EEZ has water depth <60 m, which is the boundary used here for delineating floating and fixed foundations and 10% has water depth > 227 m. Using these boundaries, the UK-EEZ has been divided into three water depth ranges: shallow (0–60 m), deep (60–227 m) and very deep (227–1000 m) water. For the distance to shore, as shown by the cumulative distribution function in Fig. 16c, half of the total seabed area is closer than 48 km to shore, and only 10% is located further than 197 km from shore. Fig. 16c also shows the variations by sea region.

The range of constraints and availability level over each sea region is shown in Fig. 17. Fig. 17a shows the cumulative total space, *A* by increasing constraint over the full UK-EEZ. The same data is also shown separately by water depth band, and in Fig. 17b is shown normalised by the total sea area. This quantifies the reduction in crowdedness as water depth increases: ~90% of the intermediate and deeper water is classified as *equally crowded* or *less crowded* than current OW sites or *clear water*, whereas only ~50% of shallow water falls into these categories.

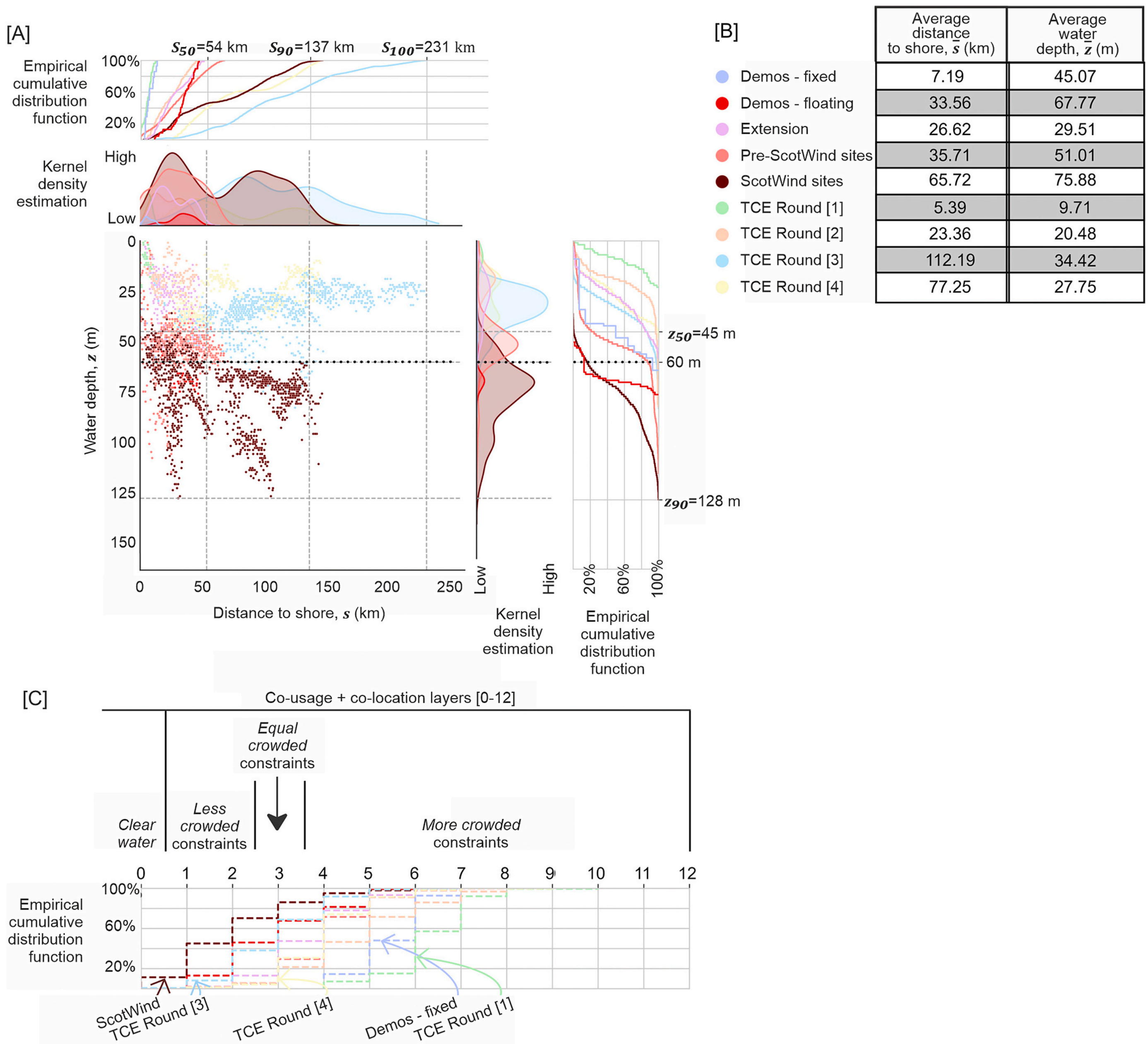


Fig. 15. Water depth, z, distance to shore, s, and the availability level characteristic of the current OW leased sites: [A] z and s in scatter plot, kernel density estimation, and empirical cumulative distribution function, [B] $\bar{z}$ and $\bar{s}$ for each site, and [C] *co-usage* + *co-location* layers of each site in empirical cumulative distribution function.

The same characteristic is shown in an alternative format in Fig. 17c, which illustrates the proportions of each water depth that make up the sea area with each number of constraints. For the *clear water* and *less crowded* availability levels (i.e., 0–2 constraints) > 80% of the available sea area is in the deep or very deep zones.

7.1. Areas of each constraint level

There are ~83,000 km^2 of *clear water* (i.e., 0 constraint layers) in the UK-EEZ (Fig. 17a), 94% in deep water, distributed by sea region as shown in Fig. 18a. The Celtic Sea, the North Atlantic Ocean, the Scottish North Sea, and the English North Sea, are the top four regions for *clear water* areas (Fig. 18a–c).

Compared to *clear water*, there is twice as much space (~160,000 km^2) that is *less crowded* in constraint, primarily in deep water (Fig. 18d–f). This space is predominantly found in the North Atlantic Ocean, Scottish North Sea, English North Sea, and Celtic Sea, in deep water (Fig. 18e–f).

The next level of crowdedness is *equally crowded* (=3 constraints) and occupies ~82,000 km^2 (Fig. 19a–c), of which 60% of which is in deep water, with the remainder split equally between shallow and very deep. Finally, the *more crowded* (>3) areas occupy a further ~80,000 km^2 and the majority of these lie close to shore in shallow water (Fig. 19d–f).

8. Scenarios of installed OW for net zero in 2050

The availability analysis was used to set out scenarios for ocean space usage and OW capacity across UK sea regions by 2050. The additional capacity was distributed according to availability levels.

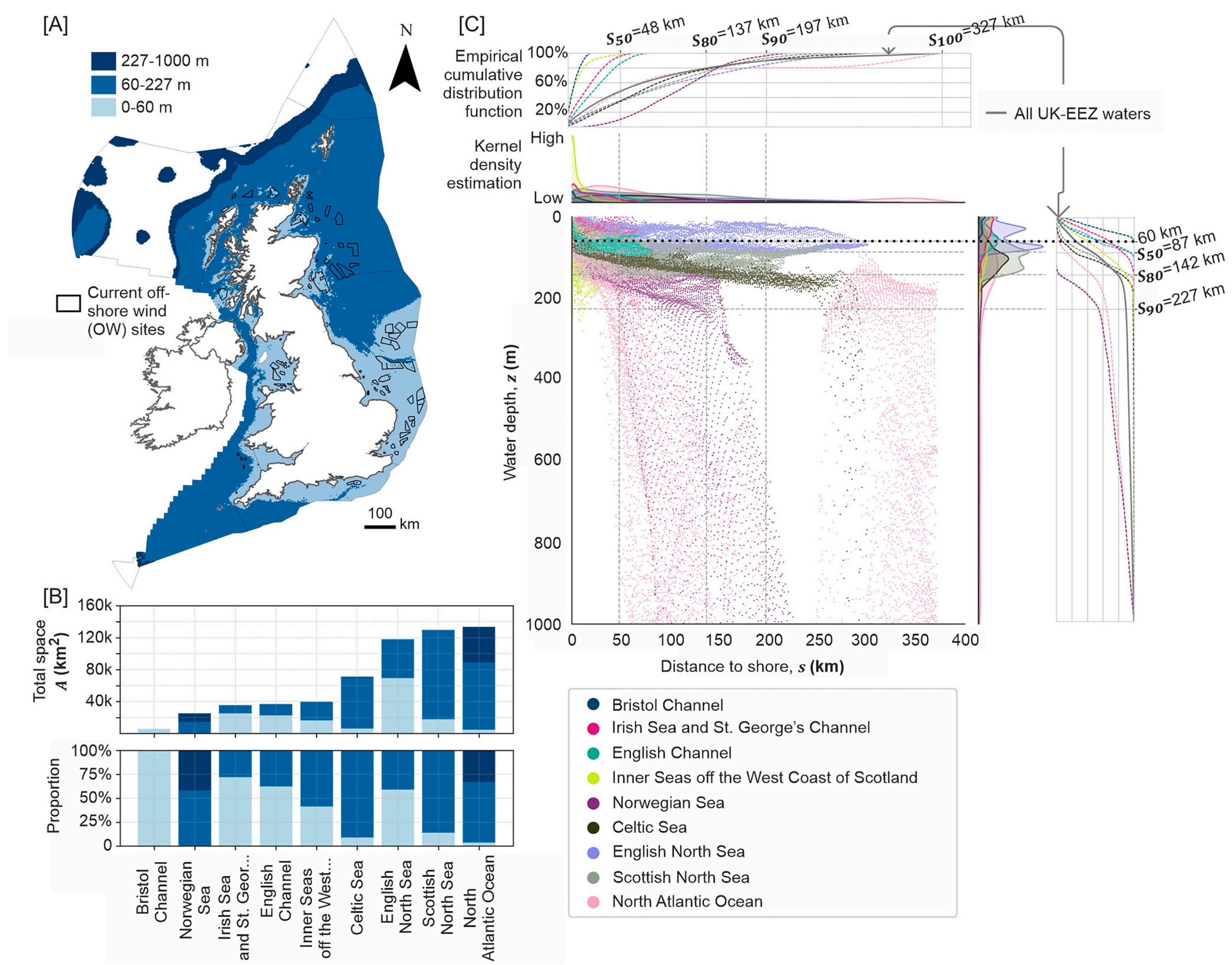


Fig. 16. Water depth, z and distance to shore, s characteristic of the UK-EEZ waters outside the current OW leased sites: [A] in map, [B] total space, A and proportion for each water depth range in each region, and [C] z and s in scatter plot, kernel density estimation, and cumulative distribution function.

8.1. Basis for 2050 deployment scenarios

The basis for 2050 deployment scenarios was derived from the following approach:

- Net zero scenarios A-C (Figs. 4 and 6) are used to define the required ocean space,
- The available ocean space excludes *no go* areas, and also areas deeper than the 90th percentile of water depth, z, and with a distance from shore, s, greater than the 90th percentile. Together, these limits of $z<227$ m, and $s<197$ km eliminate a further ~10% of the UK-EEZ, most notably the territory close to Rockall, which is highly unsuited to OW due to the remoteness and harsh ocean conditions.
- New OW developments are distributed evenly between sea regions in proportion to the available space in each region,
- Four future OW cases are considered, in which the required OW capacity is distributed across ocean space defined by different limits of co-usage and co-location:
  - o Future OW is in *clear water* only
  - o Future OW is in *clear water* and *less crowded* space
  - o Future OW is in *clear water* and *less-* and *equally-crowded* space
  - o Future OW is in *clear water* and *less-*, *equally-* and *more-crowded* space

8.2. Results of 2050 scenario modelling

For each of these four available space cases and the different net zero scenarios, the analysis shows the proportion of the available space that is required for OW (Table 3). Two key combinations are the maximum demand of Scenarios A to C, and the use of ocean space with availability levels up to *less crowded* and up to *equally crowded* relative to existing OW. For these two key combinations, the installed capacity and ocean area utilised in each sea region are shown in Figs. 20 and 21.

The utilised space proportions in Table 3 provide in a single figure an indication of the space required for OW in light of the associated space constraints and net zero targets. A utilisation proportion of 100% is never possible because some of the available space is in the form of small isolated sea regions, in some cases bounded by no-go regions, which cannot form part of a viable wind farm development. Also, as is evident from current wind farm leases, some buffer of ocean space is required between wind farms for a navigation channel, so some proportion of ocean space will always remain unleased.

Table 3 shows that future OW cannot utilise only clear water zones, especially for high demand scenarios, since the utilisation proportion exceeds 100%. The most relevant availability levels are up to *less-crowded* and up to *equally-crowded*, with the latter being *co-usage* and *co-location* comparable to existing OW leases. It might be expected, though, that a continued level of *co-usage* and *co-location* may prove unrepresentative of the future as utilisation increases. This is because some *co-*

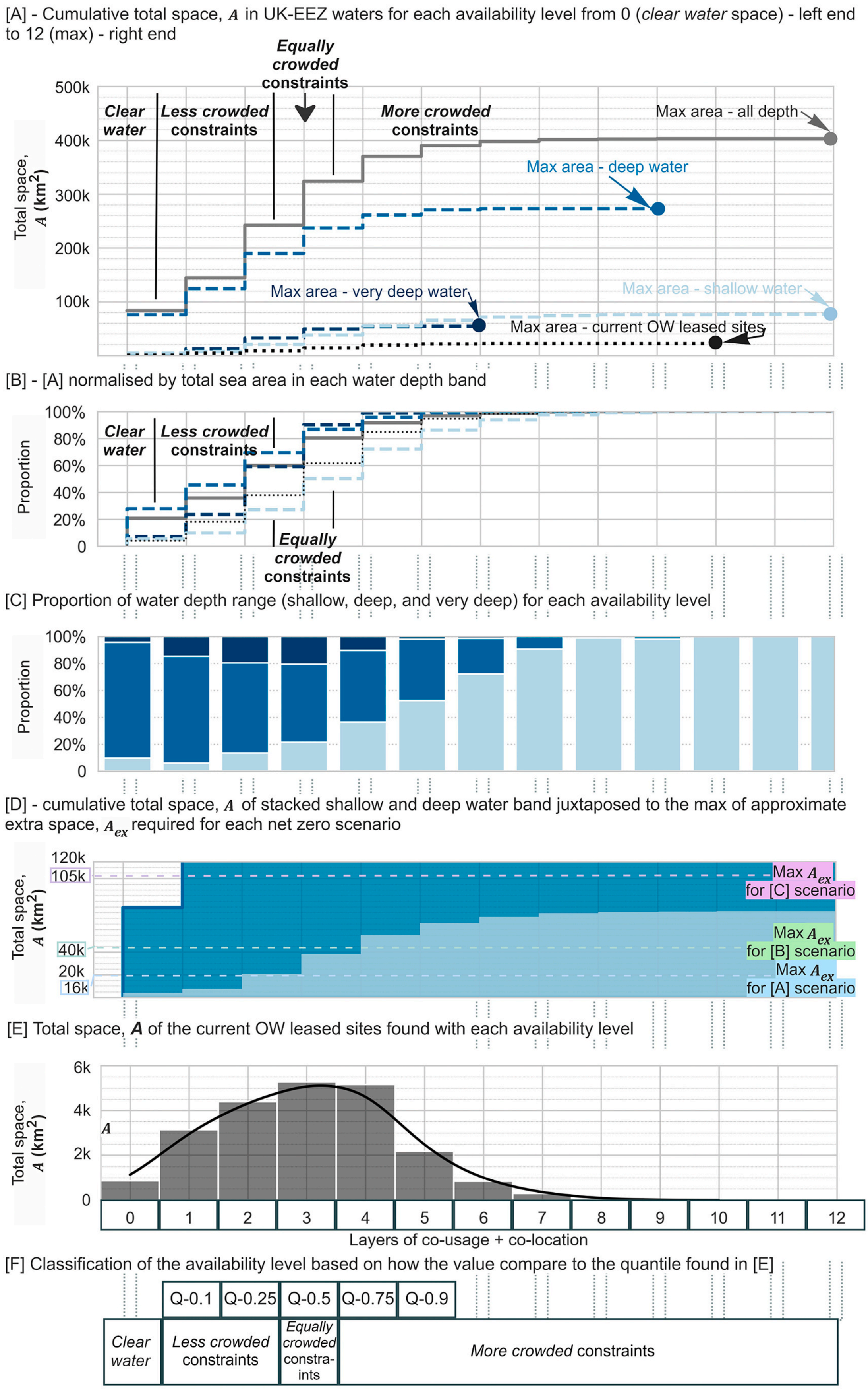


Fig. 17. Availability level in the UK-EEZ waters and the classification based on the current OW leased sites data.

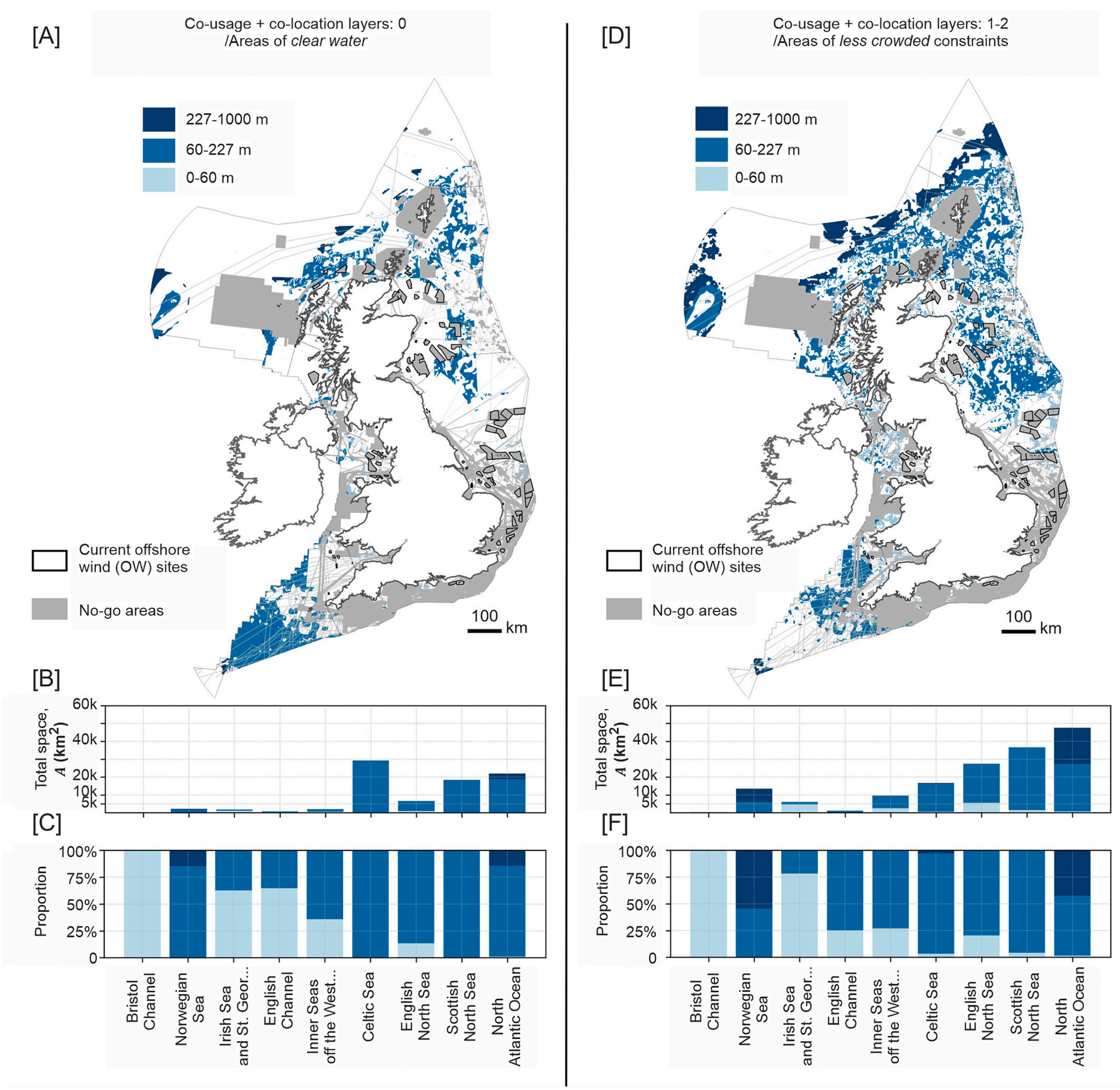


Fig. 18. *Clear water* and *less crowded* space: [A/D] in map, [B/E] total space, $\boldsymbol{A}$ and [C/F] proportion for each water depth range in each region.

usage or *co-location* can be acceptable because activity is displaced to adjacent sea regions. As the utilisation proportion increases, adjacent sea regions are less available for displaced activity. Therefore, we have highlighted both the *up to less-crowded* and *up to equally-crowded* availability cases in Figs. 20 and 21 as most representative future scenarios.

These two availability cases, combined with Scenarios A to C at maximum levels of OW deployment, require between 7% and 57% utilisation of the available ocean space for OW, and provide future extra OW capacities needed, $\boldsymbol{P_{ex}}$ in each sea region that are an appropriate starting point for planning the wider challenges and opportunities of the UK's future OW (Figs. 20 and 21). The total $\boldsymbol{P_{ex}}$ of each Scenario (A-C) (Figs. 20 and 21) equals to OW capacities needed by 2050, $\boldsymbol{P_{2050}}$ on each scenario minus a combination of existing OW capacity, $\boldsymbol{P_{existing}}$ (11 GW) and estimated OW capacity at current leased sites, $\boldsymbol{P_{leased}}$ (69 GW) [36].

8.3. Discussion of 2050 scenario modelling

These outcomes quantify the scale of the challenge to meet the net zero targets of Fig. 4. The capacities in each sea region and the space utilisation proportions convert the UK targets into regional targets and give levels of ocean *co-usage* and *co-location* that can be tested for viability for each region. For example, the Celtic Sea emerges as a key new region for which 10–84 GW of OW is projected to be required by 2050 (Figs. 20 and 21), as well as the associated port and grid connections. These projections indicate the continued acceleration of OW

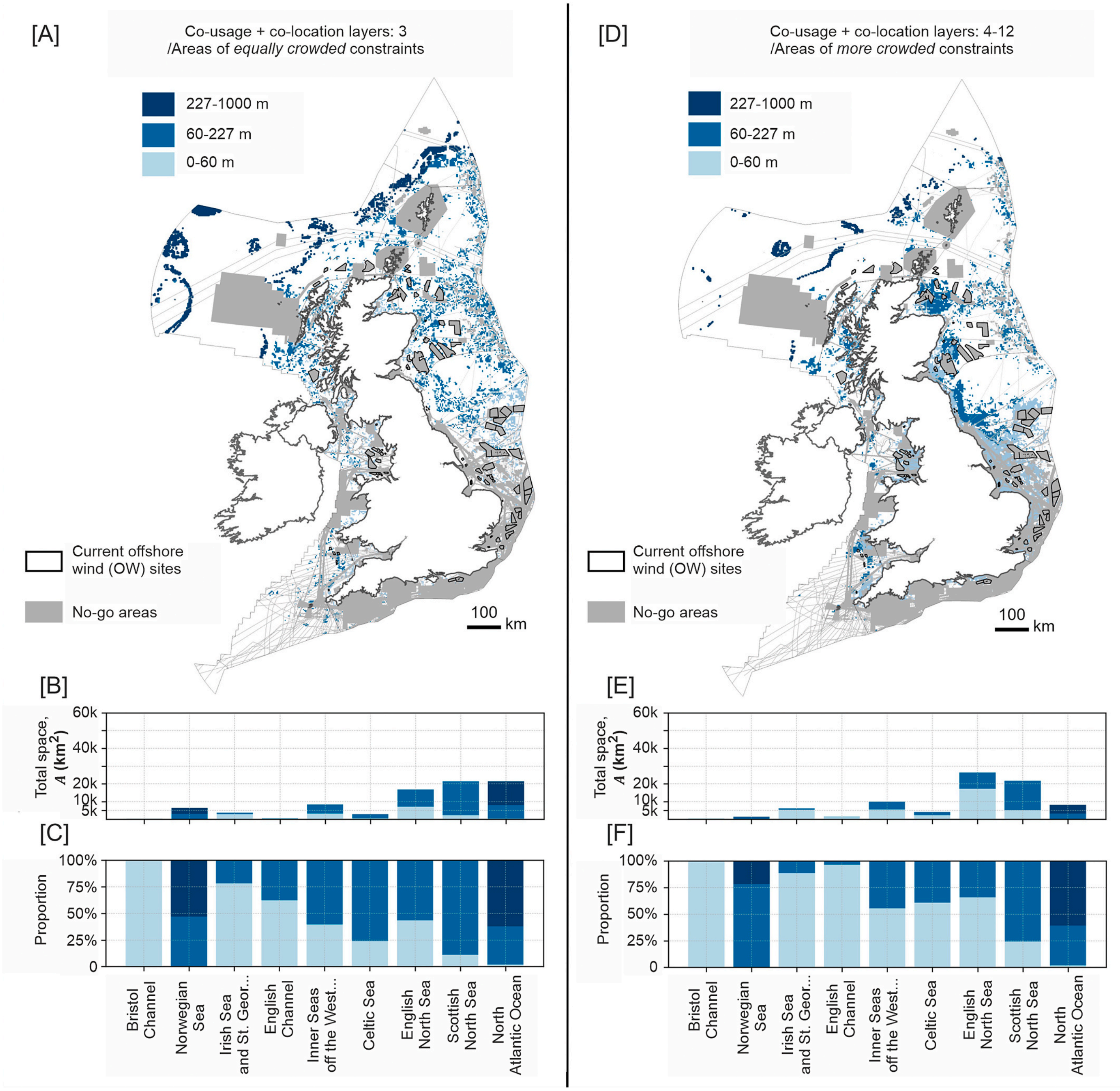


Fig. 19. *Equal crowded* and *more crowded* space: [A/D] in map, [B/E] total space, ***A*** and [C/F] proportion for each water depth range in each region.

deployment beyond the current Celtic Sea target of 4 GW of floating wind by 20,35[5], which itself requires major new infrastructure, supply chain and grid connectivity investments [42].

The outcomes of this analysis can also be applied to technology deployment horizons. For example, the scenarios in Figs. 20 and 21 indicate that 51–349 GW of the 2050 capacity, or 86–90% of the total, will be in deep water where floating facilities are favoured. Similarly, 8–90 GW (14–23%) of the 2050 capacity will be in sea regions where only a thin layer of sediment (<5 m) is present at the seafloor, presenting challenges for foundation, anchoring and cable burial that have rarely been encountered previously.

Finally, the utilisation proportions derived from this study show that if OW deployment remains focused on favourable sea regions ($z < 227$ m, $s < 197$ km) with equal or less constraints than current OW sites, these regions will become 17–57% utilised by OW, for the net zero scenarios with higher levels of OW (scenario B/C). This high proportion of ocean space featuring *co-usage* and *co-location* with OW creates potential cumulative impacts – positive and negative – on both anthropogenic activities and ecosystems. The current state-of-practice of ecological cumulative impact assessments (CIAs) is recognised as weak [43,44], and the impact of interactions between OW facilities and ecosystems vary between locations [45]. There also remains uncertainty in many aspects of offshore infrastructure-ecosystem interactions, including the net effect of infrastructure on ecosystems [46–49]. These uncertainties and states-of-practice require urgent resolution because

[5] https://www.thecrownestate.co.uk/en-gb/media-and-insights/news/2022-the-crown-estate-announces-areas-of-search-to-support-growth-of-floating-wind-in-the-celtic-sea/

Table 3
Space need at each availability level to meet the total required extra space.

Demand scenarios →	Scenario A Electricity Generation for UK demand			Scenario B Electricity Generation + Green Hydrogen for UK demand			Scenario C Electricity Generation + Green Hydrogen for UK demand and energy export		
Extra space required in each sub-scenario	Min: - km^2	Mid: 4 k km^2	Max: 16 k km^2	Min: 8 k km^2	Mid: 20 k km^2	Max: 40 k km^2	Min: 73 k km^2	Mid: 85 k km^2	Max: 105 k km^2
Availability level cases ↓ (with limits of: (i) water depth <227 m and (ii) distance to shore <197 km)	Percentage of space needed to be used from each availability level case (left side) to fulfil required extra space in each sub-scenario (above)								
Clear water space only [total space: 70 k km^2]	–	6%	23%	11%	29%	57%	**104%***	**121%***	**150%***
Clear water + less crowded space [total space: 183 k km^2]	–	2%	**9%****	4%	11%	**22%****	40%	46%	**57%****
Clear water + less and equal crowded space [total space: 241 k km^2]	–	2%	**7%*****	3%	8%	**17%*****	30%	35%	**44%*****
Clear water + less, equal, and more crowded space [total space: 312 k km^2]	–	1%	5%	3%	6%	13%	23%	27%	34%

* Cases where the space available from the availability level constraint is not sufficient to fulfil the extra space requirement.
** These percentages are used to define the space/GW needed from each sea region in Fig. 20.
*** These percentages are used to define the space/GW needed from each sea region in Fig. 21.

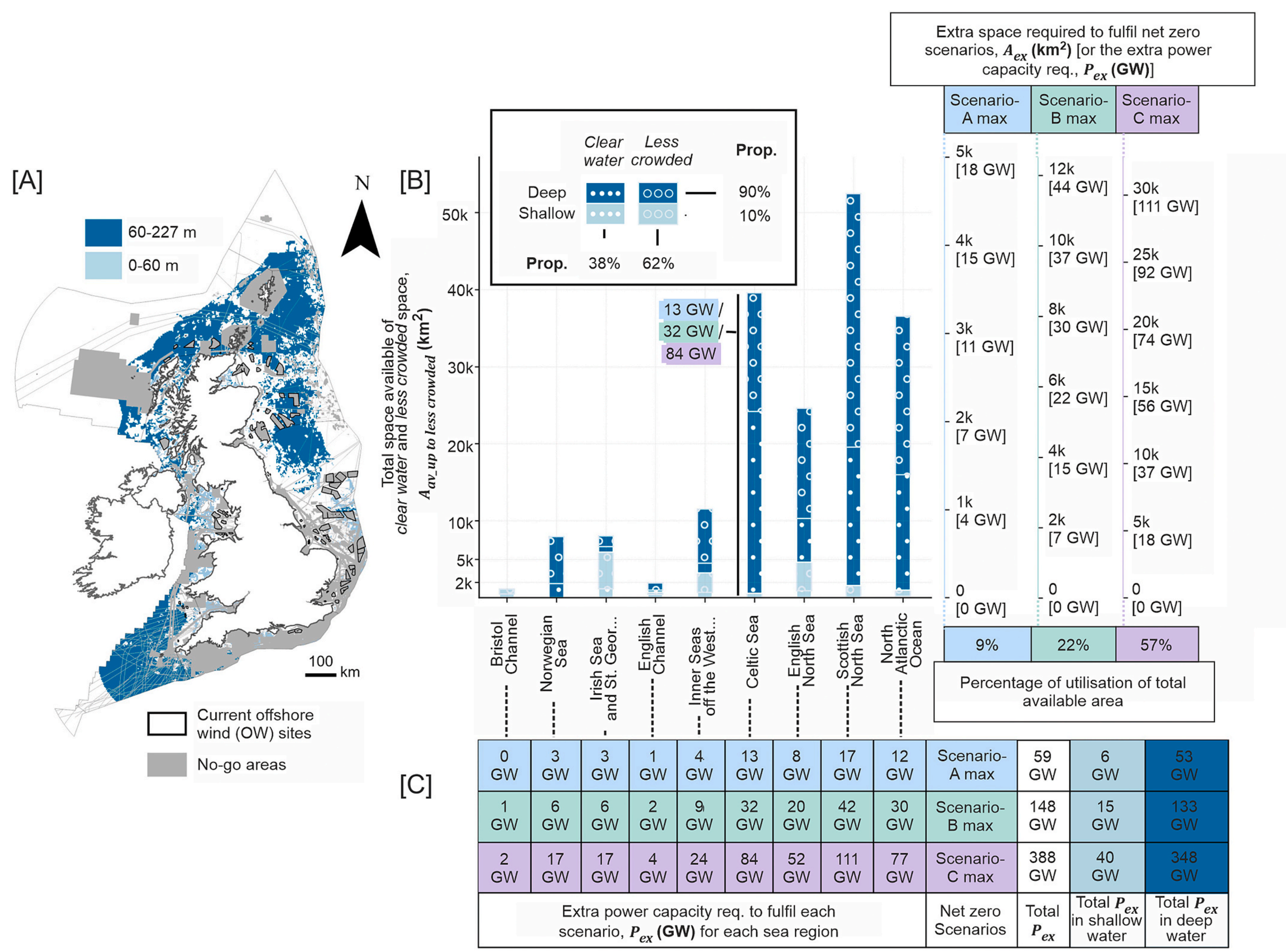
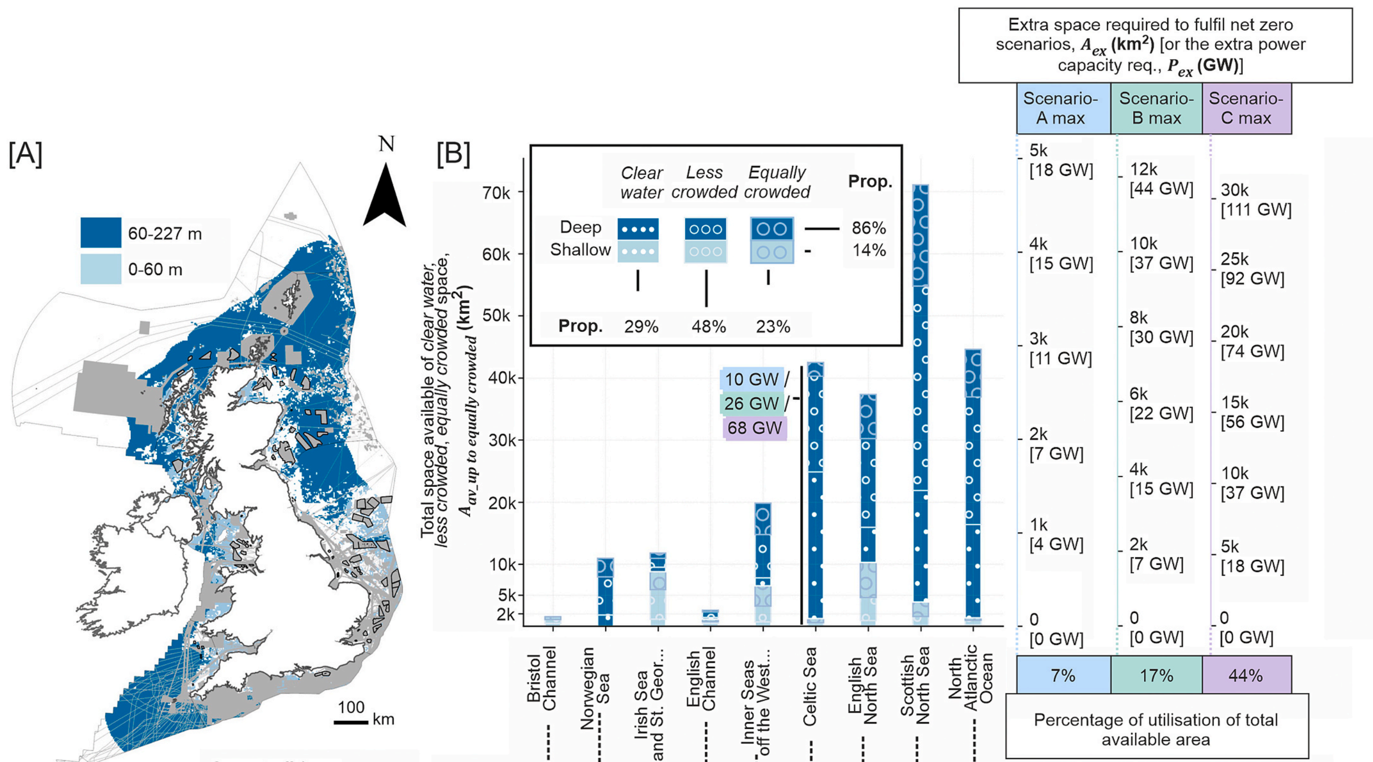


Fig. 20. Future option 1: New OW distributed across availability levels up to less crowded: [A] Total available space $\boldsymbol{A}$ in map, [B] bar charts of $\boldsymbol{A}$ (left-axis) with required extra space $\boldsymbol{A_{ex}}$ (right-axis) and required extra power capacity $\boldsymbol{P_{ex}}$ for different scenarios A-C max, and [C] table of $\boldsymbol{P_{ex}}$ for each water range and net zero scenario. $P_{ex} = A_{ex} \cdot Mdn_{\rho,S=9D_r}$, where $Mdn_{\rho,S=9D_r}$, median of ρ where $S = 9D_r$ from 2020 to 2050 is 3.7×10^{-3} MW/km^2 (see Fig. 5) and $Total\ P_{ex[Scenario\ A-C]} = P_{2050[Scenario\ A-C]} - (P_{existing} + P_{leased})$, where P_{2050} for each scenario and $P_{existing}$ & P_{leased} can be seen on Fig. 4d.



[C]

Bristol Channel	Norwegian Sea	Irish Sea and St. Geor...	English Channel	Inner Seas off the West...	Celtic Sea	English North Sea	Scottish North Sea	North Atlantic Ocean	Net zero Scenarios	Total P_{ex}	Total P_{ex} in shallow water	Total P_{ex} in deep water
0 GW	3 GW	3 GW	1 GW	5 GW	10 GW	9 GW	17 GW	11 GW	Scenario-A max	59 GW	9 GW	51 GW
1 GW	7 GW	7 GW	2 GW	12 GW	26 GW	23 GW	44 GW	27 GW	Scenario-B max	148 GW	21 GW	127 GW
2 GW	18 GW	19 GW	4 GW	32 GW	68 GW	60 GW	114 GW	72 GW	Scenario-C max	388 GW	56 GW	332 GW
Extra power capacity req. to fulfil each scenario, P_{ex} (GW) for each sea region												

Fig. 21. Future option 2: New OW distributed across availability levels up to equally crowded. [A] Total a/vailable space A in map, [B] bar charts of A (left-axis) with required extra space A_{ex} (right-axis) and required extra power capacity P_{ex} for different scenarios A-C max, and [C] table of P_{ex} for each water range and net zero scenario. $P_{ex} = A_{ex} . Mdn_{\rho, S=9D_r}$, where $Mdn_{\rho,S=9D_r}$, median of ρ where $S = 9D_r$ from 2020 to 2050 is 3.7×10^{-3} MW/km² (see Fig. 5) and $Total\ P_{ex[Scenario\ A-C]} = P_{2050[Scenario\ A-C]} - (P_{existing} + P_{leased})$, where P_{2050} for each scenario and $P_{existing}$ & P_{leased} can be seen on Fig. 4d.

the high levels of utilisation quantified in this study introduce greater potential for cumulative (i.e., multi-farm) impact effects.

9. Conclusions

A new assessment method has been developed to address the question – What ocean space is available for future offshore wind development, allowing for co-usage and co-location with other ocean activities and features? The method has been applied to the UK-EEZ, which offers an insightful case study due to the mature OW industry and the quantified targets of offshore wind growth to meet net zero targets.

A spatial analysis combining met-ocean, geological, ecological, and anthropogenic constraints enables creation of a quantitative map of availability level, such that the proportion of this space required to meet net zero targets can be determined. The availability level is quantified by the number of co-usage or co-located constraints and existing wind farms provide a basis to calibrate the number of constraints (the 'crowdedness') that is currently accepted at OW sites.

To explore two future options, the space available for future OW in the UK-EEZ has been examined, limiting future development to ocean space that is *equally*- or *less-crowded* compared to current OW sites. On this basis, future OW to meet net zero could require over 50% of the available space in the UK-EEZ. This level of utilisation and the resulting distribution of new OW development brings several novel challenges and opportunities, relevant to multiple stakeholders and other geographical regions: (i) new sea regions must be developed, with associated supply chains, ports and grid connections, (ii) heightened levels of ecosystem – wind farm and human use – wind farm interaction will occur, and must be predicted to assess their acceptability and (iii) the technological challenges will evolve – such as the need for remote maintenance, large scale floating wind and increased development on rocky seabed.

By quantifying the scale of these challenges, the methodology has practical value to industry and policymakers. The UK case study highlights how the results can provide region-specific forecasts of future shifts in the technological and supply chain requirements of OW. These shifts are driven by the changes in environmental conditions as well as the changing constraints and co-usages of ocean space. These forecasts of future OW deployment can be extended to requirements of port and grid infrastructure and can feed into wider technoeconomic forecasts that cover workforce, material, and manufacturing requirements as well as gross value added.

An interactive map, developed as part of this study and made freely available, allows free access to the underlying constraints and availability level map to catalyse further interrogation, refinement, and development of this work. While tested for the UK, the approach adopted here can be applied to any region in the world. Through openly sharing both the results and methods of work like this the global community can work together towards an enhanced understanding of what is possible and desirable with regards to OW development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link/DOI for the geospatial database used to work in this paper in the manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113358.

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