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Competition, conflict and consequences: Offshore geospatial planning for the energy transition

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Abstract

The energy transition is driving an intense, yet largely unrecognised competition for offshore space. An increasing number of conflicts have emerged between renewable technologies, climate compatible carbon mitigation and the existing claims and interests of numerous stakeholders. Using the English sector of the North Sea as an exemplar for offshore geospatial planning, we investigate the factors that influence subsurface, seabed, water column and airspace use to demonstrate challenges that impact the management of offshore areas. Crucially, the oft-ignored role of the subsurface for energy security and geological storage to aid decarbonisation highlights the need to identify and reserve key resources. The results show that an interdisciplinary approach is needed to enable the effective and equitable use of offshore areas and develop dynamic spatial planning solutions. Adoption of a data-led, evidence-based strategy ensures trade-offs and opportunities are identified, understood and addressed through technically informed decision making. The outcomes help determine primacy in the event of sectoral conflicts to achieve a managed, orderly and just transition. They are transferable to other areas of the UK's Exclusive Economic Zone and applicable in other countries. In the UK, establishment of a single overarching regulatory body and introduction of a unified licensing regime would help ensure spatial challenges are recognised and resolved. The failure to address current deficiencies, weigh up alternative uses and shape priorities will inhibit the UK's renewable energy ambitions, impact offshore safety, threaten the country's ability to meet its net zero targets and delay the energy transition.

Supplementary material: Appendix A (Data sources), Appendix B (Acronyms and definitions) and Appendix C (Fishing activity overview) are available at: <https://doi.org/10.6084/m9.figshare.c.8443950>.

Context and Aims

Robust, reliable, resilient and secure energy supplies are vital to power nations and their industrial centres, reduce fuel poverty, enhance quality of life and promote well-being. Traditionally provided by fossil fuels, emissions from the supply and consumption of coal, oil and gas contribute to climate change and present a major global challenge (e.g. IPCC, 2018). While it is possible to achieve emissions reductions and decarbonise through the closure of power stations, industrial clusters and the coal, oil and gas sectors, deindustrialisation comes with a cost to jobs, Gross Domestic Product (GDP) and a loss of strategic assets. The consequent import of materials and products that modern society demands (cement, oil and gas etc.) also brings a higher carbon footprint and is detrimental to global climate goals. Key challenges for the energy transition therefore centre on how to maintain or enhance energy supplies, keep them affordable, whilst being environmentally sustainable and climate compatible, the so-called “energy trilemma”.

The UK’s legally binding commitment to net zero by 2050 lends a sense of urgency to weaning the country off its dependence on oil and gas, which currently account for 75.2% of primary fuel consumption (resources before they are transformed into useful energy), (Fig.1a) (DESNZ, 2025a, Chapter 1). Progress in the power sector saw the share of renewable electricity supply grow from 19% in 2014 to 48% in 2024 (Fig.1b). With a clean power target of 95% low-carbon electricity generation by 2030 (UK Government, 2024), plans are being laid to further transform the energy system through a greater use of low carbon or renewable electricity while simultaneously promoting electrification (Fig.2). Consequently, there is an expectation that the future high demand for electricity will primarily be met by offshore wind, the use of which necessitates a major expansion and upgrade of the UK’s electric power transmission network (House of Commons Environmental Audit Committee, 2024; International Energy Agency, 2024; National Grid ESO, 2024).

In parallel, recognition of the need to decarbonise industry, yet safeguard jobs, led the Committee for Climate Change (CCC) to conclude that there is no route to the UK’s goal to achieve net zero by 2050 without deploying carbon capture, transportation and storage at scale (CCC, 2020). It has been estimated at 50% probability (P50, or ‘as likely as not’), that 78 GT of geological storage is available beneath the UK Continental Shelf (UKCS) (Bentham *et al.* 2014; NSTA, 2025a). If this figure is confirmed, this could enable the decarbonisation of UK domestic industry and allow the development of commercial models that permit the country to receive imports of carbon dioxide to store in future.

With the current government’s goal to make Britain a global energy leader expressed through its ‘Clean Energy Superpower Mission’ (CESM) there is a clear intent to deliver clean power by 2030 and accelerate to net zero by 2050 (DESNZ, 2025e). The targets for up to 50 GW of offshore wind and capture and storage of 20-30 Mt CO₂/year by 2030 (HM Government, 2022, 2023a, 2024), will mean significant investment in the UKCS will be required to support the energy transition.

Recognition that CO₂ storage targets will demand a continual maturation of suitable sites for development, nomination of additional stores and future licensing rounds will result in increased spatial pressures offshore. Whilst it is technically possible to co-locate wind farms above proposed carbon storage sites or existing gas operations, technical, regulatory, insurance and indemnity issues have already led to conflicts (Underhill, 2021). Consequently, unless co-location strategies can be developed, there appears to be an

effective mutual exclusivity between the technologies. This is best demonstrated by the fact that only areas unaffected by a wind farm footprint were offered in the first carbon storage licence round.

The use of offshore space is further complicated by the presence of other well-established stakeholders and sectors which hold interests and claims to the subsurface, seabed, water column and airspace. This 'spatial squeeze' results in overlap and competition between users. The situation raises important questions around the allocation and management of offshore activities, regulation and which technology or use should receive primacy in the event of conflict. Progressing the development of offshore-based low-carbon technologies alongside other marine sectors therefore requires a shift from conceptual approaches (e.g. Quirk *et al.* 2022) and departure from allocation of areas on a first-come-first-served basis. Instead, solutions founded on understanding practical elements and interconnectedness of offshore use can be used to guide and improve future decision-making (e.g. Bates, 2017, Randall *et al.* 2021). A failure to recognize and resolve these issues will inevitably lead to unwelcome conflict and seriously jeopardize the UK's ability to improve energy security, achieve stated emissions targets, decarbonize industry and meet its net zero obligations.

With a clear focus on seabed and subsurface use, the English sector of the North Sea is used as an exemplar of the 4D offshore spatial planning challenge. The aims of this paper are therefore to 1.) review the factors that influence present and future offshore activity; 2.) identify spatial requirements to determine compatibility and ability to co-locate with other marine users; 3.) recognise the challenges and inevitable consequences resulting from overlapping claims and interests; 4.) explore options, trade-offs and propose spatial solutions to address regulatory challenges; 5.) ensure the best and most appropriate use of the marine area; and 6.) respect the communities that depend on the offshore environment for their livelihoods.

Emissions reduction and industrial decarbonisation

Ambitious and legally binding targets introduced by the UK government in 2019 include reduction of greenhouse gas (GHG) emissions by 68% relative to 1990 levels by 2030, 81% by 2035 and net zero emissions by 2050 (DESNZ, 2022, 2025d). Between 1990 and 2023, total territorial (within border) GHG emissions fell from 810.7 to 385 Mt CO₂e, representing a 52.5% reduction over the past three and a half decades (Fig.3). Success to date has seen the UK decarbonise faster than any other G7 country and exceed its initial carbon budgets. This has been achieved through changes in the power sector due to the country's pivot away from coal, increased use of renewables and improvements in energy efficiency (Figs.1 & 2), (DESNZ, 2025b; HM Government, 2023).

Although industrial GHG emissions have reduced by a third since 1990, the relative component of CO₂ has increased from 76% to 97% of total emissions from this sector, accounting for 51.5 Mt CO₂ in 2023 (16.5% of the UK's total CO₂ emissions), (DESNZ, 2025c), (Fig.3). High temperature industrial processes and use of carbon-rich raw materials mean that the highest emitting 'heavy industries' (cement, steel and chemicals), will be the most challenging to transition away from fossil fuel feedstocks (Gabrielli *et al.* 2023; IEA, 2020; The Royal Society, 2024). Carbon Capture and Storage (CCS) is therefore expected to play an important role in reducing industrial emissions (CCC, 2020) and a target to

capture and store 3 Mt CO₂ from industry per year by 2030 is outlined in the UK's industrial decarbonisation strategy (2021).

Repurposing the basin for carbon storage

A comparison of historical point-source emissions from power and other sectors (Fig.4a & b) highlights the lasting presence of hard to decarbonise sites located in the UK's industrial heartlands (e.g. in and around Humberside, Teesside, South Wales, Merseyside and the Solent). In the offshore waters of the Southern North Sea (SNS), numerous depleted gas fields and saline aquifer sites could provide a carbon sequestration solution for 50% of the UK's industrial cluster emissions either via pipeline or shipping solutions (Brook *et al.* 2003; Bentham *et al.* 2014; East Coast Cluster, 2025; Gibson-Poole *et al.* 2024a; Gluyas & Bagudu, 2020; Holloway *et al.* 2006; Underhill *et al.* 2023; Viking CCS, 2025a). Similarly, plans to decarbonise 40% of the UK's cement and lime production include deployment of CCS to link emissions from industrial sites within the 'Peak Cluster' to the Morecambe Net Zero (MNZ) subsurface storage site in the East Irish Sea (MNZ, 2025; Peak Cluster, 2025).

The opportunity for CCS has led to two of the four existing carbon storage licences in the English North Sea entering the UK government's track process, of which, the Humber and Teesside 'East Coast Cluster', has been selected to benefit from the recent £21.7bn pledged to kick-start the CCS industry in the UK (DESNZ, 2024). Underlining the importance of the SNS for CCS, a subsequent 14 (of 21) licence awards were made in the area in the first offshore carbon storage licensing round (Fig.4b). These projects are now undergoing critical evaluation and appraisal before a Final Investment Decisions (FID) are taken. Viable projects will then be awarded a storage permit award prior to operations and CO₂ injection commencing (NSTA, 2023a). Further carbon storage areas have since been nominated and a second licensing round was announced in December 2025, the outcome of which will further increase spatial pressure in offshore areas.

Spatial Planning

The term Marine Spatial Planning (MSP) is rooted in ecosystem-based management of the marine environment (e.g. Douvere, 2008). The concept has evolved to include knowledge sharing and data integration, marine protection and restoration, sustainable growth of the 'blue economy' and reduction of conflict (e.g. Ehler, 2021, Reimer *et al.* 2023). MSP has been explored in the UK (e.g. Boyes *et al.* 2007; Vincent *et al.* 2004) and recognised as a tool for planning and decision-making in order to '*avoid, minimise or mitigate*' the impact of multi-sectoral offshore use (Marine Policy Statement, HM Government, 2011). The first marine plans were published in England (MMO, 2014) and Scotland (Scottish Government, 2015) which predate UK legislation on net zero (2019) and the introduction of policy to enable rapid progression of nationally significant infrastructure projects (NSIPs) including energy developments (DESNZ, 2023; Planning Act 2008, Part 3).

Spatial planning is a dynamic process involving the temporal evolution of space as sectors evolve and the need for them changes. Approaches to MSP taken by different countries include the use of zoning to prioritise areas for individual activities, thereby preventing conflict and allowing conservation objectives to be met in separately defined areas, e.g. in Australia since 1981 (Day *et al.* 2018); Germany (BSH, 2023); Netherlands (Government of the Netherlands, 2015). Recognising the rapid change in societal demands over the last two

decades, legislation in the Netherlands means MSP is regularly adapted to reflect new experience and knowledge while supporting a long-term strategic vision (de Vrees, 2021; Government of the Netherlands, 2022). For example, recognising a slower transition from oil and gas (primarily for the electrification of industry), and lower projected overall demand for electricity, alongside high construction costs have recently led to offshore wind targets being scaled back in The Netherlands (Netherlands Enterprise Agency, 2025). To optimise use of valuable offshore space for the UK's energy transition, it will therefore be essential to improve cross-sectoral awareness to inform a range of scenarios reflecting future wind and subsurface storage needs.

Traditionally used in addressing land suitability problems (e.g. Malczewski, 2004), spatial analysis methods have more recently been applied to aid offshore planning and determine suitability and space for offshore wind (Madsen *et al.* 2012; Jongbloed *et al.* 2014; Putuhena *et al.* 2023; Randall *et al.* 2021). However, there is a need to address limitations, including those within the current UK marine plans, which neglect to consider potential suitability of the surface or subsurface areas for future use. To integrate, include and emphasise the important role the subsurface will play in meeting the UK's energy needs and delivering emissions reductions, we introduce and use the term *Offshore Geospatial Planning (OGP)* in this paper. This is to distinguish it from traditional Marine Spatial Planning (MSP) used in previous studies as that tends to *omit* the subsurface from the analysis, something we are keen to rectify.

Competition for offshore space

Historically, the North Sea area has experienced multiple changes in use associated with thousands of years of human activity. Fishing, development of maritime trade and in the last century, a zone of confrontation during WWI and WWII all contribute to the archaeological and historical importance of the region. From the late 1960's, the geological significance of the area became evident. Discovery and extraction of oil and gas resources led to extensive development activity and the North Sea became one of the world's most explored basins (King, 2020). Introduction of the Continental Shelf Act (1964) enabled licensing of oil and gas activities beyond the 12 nautical mile limit of territorial sea (up to 200 nautical miles, or the edge of the continental margin). The discoveries that followed provided energy security and resulted in a profound impact on the UK's economy.

Today, the North Sea area has a key role in the energy transition of the countries bordering it due to its suitability for offshore wind and large potential capacity for subsurface storage of carbon dioxide, natural gas and hydrogen. However, deployment of offshore wind requires access to large areas of maritime space. In what has since become one of the busiest offshore areas in the world, increased awareness of the importance of biodiversity and environmental protection demand active solutions. Balancing the competing needs of different stakeholders, sectors and regulators alongside the net zero ambition therefore presents a significant challenge for future offshore planning and management.

Study area and data

The English sector of the North Sea (ENS) is an area of c.118,000 km² equivalent to around 15% of the UK's EEZ in Europe. The ENS encompasses five UK Marine Plan areas defined by the Marine Management Organisation (MMO, 2014) and includes the geological

provinces termed the Southern North Sea (SNS) and a sub area of the Central North Sea, the Mid North Sea High, as defined by the British Geological Survey (BGS) (Cameron *et al.* 1992; Gatliff *et al.* 1994), (Fig.5).

Around 50% of the ENS lies in water depths of less than 50m, almost all of which is in the SNS, placing suitable depths for fixed foundation offshore wind coincident with an area of significant subsurface storage potential (Fig.4b). Due to this overlap and favourable geological conditions, several offshore wind and carbon storage sites have been recognised and the SNS region is considered to have high energy transition potential (BGS, 2025a).

Competition for the same space arises due to other use involving human stakeholders in the oil and gas industry, marine aggregate extraction, cables and pipelines, conservation, fishing, shipping, aviation and military activities; alongside several 'silent' (non-human) stakeholders including wildlife and ecosystems. To provide insights on the wider use of this crucial area for the UK's energy transition, geospatial data relating to current human activities and natural areas of importance were compiled in GIS software as a series of feature layers. Marine data for the UK is widely available in vector and raster formats from a wide range of sources, providing a total of 128 layers which were grouped and merged into 42 main layers to be incorporated into this study (Supplementary material: Appendix A). An overview of the present-day multi-sectoral human use of the subsurface, seabed, water column and airspace in the ENS area is presented in Fig.6a-d.

Spatial demand and methodology

To investigate the extent of spatial pressure in the ENS that results from human use, the spatial layers were re-projected into a common spatial reference system (ED50/UTM Zone 31). Polygons were merged (when and where required) and then transformed into raster format at 100m spatial resolution. Where appropriate, buffer distances determined from a review of the spatial requirements for each activity were included in the processing workflow and include operational and safety requirements based on a review of published literature. The definition of each layer as used is given in Table 1a-d.

A composite map produced from the final raster layers including their spatial requirements identifies areas with up to 12 overlaps and indicates that 73% of the total ENS area is currently important to at least three human uses (Fig.7). With a high concentration of spatial demand, 89% of the shallow (<50m) SNS or combined 'East Inshore and Offshore' marine plan area is of importance to at least three uses compared to 54% of the combined 'North East Inshore and Offshore' area. The main differences result from lower fishing, shipping, offshore wind and subsurface use in the deeper northern region. Just 4% of the northern area and <1% of the southern area are free from the claims and interests of human activity as defined in Table 1a-d. A breakdown by sector reveals that the spatial demand from human stakeholders in the total ENS is over three times the total area available (Fig.8).

The focus of this aspect of the work centres on human use of offshore areas. As areas become ever more crowded, there will be an increasing impact on the non-human users (fish, birds and mammals). Although it is beyond the scope of this work to include layers indicating individual species distribution, a review of available spatial data sets and information is shown in Table 2. The data reveals that when the interest of silent

stakeholders is included (e.g. seabird foraging areas and fish spawning and nursery grounds), there is no part of the ENS that could be considered completely free of use.

Compatibility

The diversity of spatial claims and interests illustrate the multidimensional challenge associated with OGP and the need to factor in spatial requirements to planning decisions. Overlapping sectoral interests indicate that some offshore users can co-locate however, compatibility between different sectors varies and incompatibility introduces conflict. A summary of the current understanding of offshore user interactions is shown in Fig.9. Layers were classified according to the following criteria:

- *Generally compatible (no constraints)* – Activities can take place in the same geographical area with minimal interference to each other. For example, radar and aviation are generally compatible with other sectors as most other offshore activity does not encroach into airspace, except for offshore wind.
- *Potential conflict: Co-location solutions technically possible* – Allows two or more activities to exist at the same time and in the same geographical area. Despite spatial constraints they are technically and legally able to operate within the same area through adaptation of mitigating strategies and technologies to reduce risk. In areas where co-location is possible, an indication of priority means that one activity is likely to be limited due to environmental, national security, economic or safety reasons.
- *Not Compatible* – Presence of a single use rules out any other activity occurring in the same location. Activity can only be conducted by whoever gets there first.

Marine use is constantly changing, and it can be expected that sectors will continue to evolve in response to different needs, conditions or technological innovation. Consequently, the impact of this on future spatial claims and interests introduces uncertainty into the planning process. For example, without co-location solutions, some activities may impede other users such as offshore wind and subsurface storage of CO₂ in the same area (e.g. Underhill, 2021). These activities require planning and development at an early stage to account for the need to access the subsurface throughout the lifespan of a project. Recognising this challenge for future offshore wind projects, two scenarios are considered in Fig.9 to demonstrate: 1.) the lack of compatibility between current offshore wind sites with other users, primarily related to use of the subsurface; and 2.) the potential opportunity for future offshore wind projects to be developed in a way that optimises use of the marine area through application of co-location solutions. *Regulation and Consent*

There are numerous regulatory and statutory bodies associated with each activity or sector, which introduces further complexity (Fig.10, also see Supplementary material: Appendix B). Each have evolved with their own roles, responsibilities and individual objectives that are not necessarily consistent or compatible with the multi-use use of offshore space. The disjointed approach to governance of the UK's marine area is exemplified by the remits of the North Sea Transition Authority (NSTA), The Crown Estate (TCE)/Crown Estate Scotland (CES) and Marine Management Organisation (MMO).

Subsurface use is licenced, permitted and regulated by the NSTA, following a name change from the Oil and Gas Authority (OGA) in 2022. Their remit includes oil and gas exploration and production, offshore hydrogen storage and carbon storage (Petroleum Act 1998, Section 18 of the Energy Act 2008). The mission of the OGA was Maximising Economic Recovery

(MER) (OGA, 2016), later amended in the OGA Strategy (2021) to place an additional obligation on the oil and gas industry to *'assist the Secretary of State with meeting the net zero target'*. In the case of carbon storage, a storage permit is required to progress beyond the initial (appraisal) term of the licence and into the operational phase of activity. Where it is possible that hydrocarbons may be encountered, a petroleum production licence may also be required alongside the carbon storage licence.

The UK's seabed and coastline are managed by TCE and CES with the core duty *'to maintain and enhance its value and the return obtained from it, but with due regard to the requirements of good management'* (The Crown Estate Act, 1961). Building on this, the Crown Estate Act (2025) grants borrowing and investment powers *'to grow the value of the business into the long-term and the profits it returns to HM Treasury for spending on public services'* (TCE, 2025a). TCE and CES are not regulatory bodies, but more akin to landlords who have been given a key role in leasing the seabed for offshore wind development in the UK's territorial sea and Exclusive Economic Zone (EEZ) (see Paterson, 2024 and Section 84 of the Energy Act, 2004). Large scale offshore wind farms are classified as NSIP's and a Development Consent Order (DCO) is required via the Planning Inspectorate (PI) to construct, operate, maintain, and decommission (Planning Inspectorate, 2024a). Following review and recommendation by the PI, it is the Secretary of State for Energy Security and Net Zero who is ultimately tasked with the decision to grant the DCO which for NSIPs includes a deemed marine licence from the MMO (Marine and Coastal Access Act 2009).

TCE and CES also lease areas for gas and carbon storage, aquaculture and coastal development, licence marine aggregate extraction and permit cables and pipelines. For carbon storage, an agreement for lease at the time of initial licensing through the NSTA is the precursor to an additional fee (rent) for seabed and subsurface rights in the form of a Crown Lease from TCE. A Crown Lease is required by CCS developers prior to or in parallel with gaining a storage permit from the NSTA (see NSTA, 2023a and Section 18 of the Energy Act 2008). Despite the small seabed footprint of subsurface activity, the Crown Lease area (which can also include the pipeline corridor) is expected to extend to the same limits as the NSTA CCS licence. However, the presence of an overlapping offshore wind lease can result in some misalignment (e.g. CS001, the Endurance CO₂ Storage Facility and Pipelines Site Agreement and the Hornsea-4 lease for offshore wind).

The MMO is the primary regulator for marine activities in England and Wales. With a strong focus on nature conservation and fishing the MMO seek to ensure that activities in the marine area make a *'contribution to the achievement of sustainable development'* (Marine and Coastal Access Act, 2009). Where a seabed lease from TCE or an NSTA licence grants rights of use, a marine licence may also be needed. This is required for any venture that may impact the environment including construction, dredging, deposit, removal or incineration of any substance or object, sinking of vessels or floating containers and use of explosives (MMO, 2025a). Furthermore, the MMO has additional responsibility for preparing marine plans in England.

Despite appearing to have common ground in the legally binding net zero objectives, there is an evident lack of early connection and compatibility between users and at policy level. Consequently, and with the absence of an integrated offshore geospatial plan, this has led to uncoordinated decision-making with the award of overlapping licenses and leases for the same area in several instances. The pitfalls of allocation of activities on a single-sector basis

can be highlighted in the SNS where overlaps in areas leased for offshore wind have occurred. A notable example existed where the 2009 Hornsea-4 wind lease partially overlapped with the CS001 licence area issued in 2012 (containing the carbon store now known as Endurance), (Reuters, 2023a; Underhill, 2021). Furthermore, 12 oil and gas exploration licences awarded in the recent 33rd round (2024) overlap with existing offshore wind leases in the SNS, (Dogger Bank Southwest, Southeast, Hornsea-4, Outer Dowsing, Norfolk Boreas and Vanguard East). Future potential for conflict has also been highlighted where the Outer Dowsing Wind Farm overlaps the now decommissioned Pickerill gas field (de-Jonge Anderson & Underhill, 2022). Elsewhere, in an example from the Outer Moray Firth, the Acorn carbon storage licence (CS003) and several 33rd Round oil and gas licenses are partially overlapped by the Marram Wind lease. Shifting the focus to the subsurface, 28% of Round 1 CCS licences in the ENS currently overlap with an oil and gas licence (Fig.6a). Despite the potential synergies in subsurface use and re-use, the two sectors are independently managed within the same regulator under different legal regimes (The Petroleum Act, 1998 and The Energy Act 2008 & 2023). Consequently, there is a possibility for conflict to arise where the objectives and interests of licensees misalign (e.g. abandonment strategy and remediation of oil and gas wells to enable subsurface carbon storage).

In the case of Hornsea-4 and Endurance, competition for the same area resulted in a ten-year negotiation process that failed to find a solution to allow Measuring, Monitoring and Verification (MMV) of the subsurface storage site (to image the plume and ensure storage integrity) within the area of the wind farm (Reuters, 2023b). A commercial agreement was eventually reached to resolve the conflict (Planning Inspectorate, 2023), resulting in the offshore wind lease being pared back to remove the overlap (Fig.11). However, due to rising costs, the Hornsea-4 project has since been discontinued '*in its current form*' (Orsted, 2025).

In cases where no agreement can be reached, the process is escalated to the UK Secretary of State for Energy Security and Net Zero to appoint an independent value assessor to determine the level of compensation to be paid to the renewables developer (Crown Estate Leases for Offshore Renewable Projects: Oil & Gas Clause, DECC, 2014b). More recently, an attempt to resolve spatial conflict arising between oil and gas and offshore wind has led to introduction of a co-location clause, to support coexistence of both industries (NSTA 2025c).

The need to consider all stakeholders and regulatory bodies (Tables 1, 2 & Fig.10) and factor in their complex interactions (e.g. Fig.9) prior to designating an area for specific use is also highlighted in Fig.11. Examples of the technical challenges faced can be demonstrated in the vicinity of the now shelved Hornsea-4 wind farm. They include: the presence of underlying depleted gas fields which may have potential to be repurposed for storage; the requirement to monitor the seabed above and around storage sites and neighbouring structures to ensure site integrity; the presence of a shipping route used by over 1000 vessels a year; and, the need to retain access to subsea infrastructure including legacy wells, pipelines and electricity cables which may be required to remediate leakage or damage (accidental or deliberate), all of which, in this example, occur within a marine protected area.

Recognising the need to '*balance the interests of the marine environment*' and make '*efficient use of the seabed*' has resulted in TCE's attempt to expand their role and take

greater responsibility for siting and maximising the potential of offshore wind through pre-selection of 'bidding areas' for leasing rounds (TCE, 2021). However, a review of their methodology (2019) highlights flaws in the process including assumptions around the extent and use of geographically restricted (subsurface) resources, the assumed ability to co-locate with other offshore users and failure to consider the impact of cumulative developments.

Regarding carbon storage, an NSTA technical report on 'MMV and co-location of wind and CCS projects' (2022) concluded that *'based on current technologies, large physical overlaps between carbon storage sites and wind farms are presently considered not to be feasible'*. As part of a revised effort to improve co-ordinated management of the seabed going forward, a statement of intent has since been issued between TCE and NSTA (2024) outlining a plan to proactively share data for sustainable marine development with focus on supporting CCS and *'addressing co-location challenges between key sectors, including assessing technical viability, in an increasingly busy sea space'*.

Beyond the subsurface, risk of exclusion due to offshore wind is also a recognised and understandable concern in the fishing sector where displacement of activity can introduce new conflict with other offshore users (ABPmer, 2022; Bonsu *et al.* 2024; Jentoft & Knol, 2014; Schupp *et al.* 2021). In an example from Norway, development of the world's first floating offshore wind farm (Hywind Tampen) proceeded without addressing concerns raised by the fishing industry or their recommendations to reduce overlap with trawling lanes (Utne-Palm *et al.* 2025).

In the shipping sector, lack of consultation in early offshore wind leasing highlighted threats to the environment and safety of navigation in established shipping routes and port access channels (Parliament.uk, Memorandum by the Chamber of Shipping, 2004).

Other conflicts have arisen from pressure to meet international biodiversity targets, where in Scotland, government plans to designate 10% of offshore waters as HPMA were cancelled in 2023. This was due to a high level of opposition from fishing and coastal communities fearing the impact of economic hardship (The Scottish Parliament, 2023, p.29). The emergence of these challenges alongside wider recognition of the significant increase in offshore activity and need to tackle climate change and biodiversity loss highlighted deficiencies in the Scottish Government's National Marine Plan 1 (2015), (The Scottish Government, 2021). A revised approach (National Marine Plan 2) is now underway aiming to enhance understanding of current offshore use and aid improved decision-making, while balancing the needs of the environment and communities to support a 'Blue Economy Vision' (National Marine Plan 2, 2023; Scottish Government, 2022).

In the relatively immature regulatory environment, there is still uncertainty on how regimes will interact. However, as the complex spatial and regulatory challenges become increasingly clear, the fact that conflict and inconsistency can occur raises important questions around the objectives and duties of individual licensing/leasing and consenting bodies. Specifically, questions emerge about whether they are encouraged to make the right decisions and if they have the appropriate cross-sectoral knowledge to enable informed decision making when faced with the increased competition for offshore space.

Importance of subsurface geology

A review of the methods and outcomes of previous studies related to marine planning in the UK (e.g. Boyes *et al.* 2007; TCE, 2019) reveals a surprising omission of key information relating to subsurface resources. We are not aware of any publication to date that explicitly addresses or integrates their distribution and future potential in the context of offshore planning for the UK's energy transition. Furthermore, spatial data representing current activity is subject to change from time-to-time introducing uncertainty to the wider planning challenge. This is particularly true where subsurface evaluation is required in areas licenced to explore for oil and gas or characterise a storage site prior to any major financial commitment. Licences are defined for a period and activity is generally limited to within the boundary of the licence. A licenced area does not always progress to a development or may be relinquished for economic or technical reasons (e.g. lack of site viability). Therefore, mapping of subsurface activity inferred from licenced areas can only provide a snapshot of present-day use (e.g. Fig.6a) and does not reflect the potential in currently unlicensed areas.

To address these limitations and provide insights relevant to using OGP for long-term strategic management of offshore activity, the need for subsurface geological resources is summarised alongside identification of areas with potential technical suitability for future use. With over 60 years of well and seismic data acquired to explore the offshore areas of the UKCS, much of which is publicly available via the NDR, the subsurface geology of the SNS is relatively well understood (e.g. Cameron *et al.* 1992; Doornenbal & Stevenson 2010; Doornenbal *et al.* 2022; Underhill, 2003; Underhill *et al.* 2023). Summary maps representing the geology of key intervals are shown in Fig.12a-c, each compiled from multiple sources and updated where necessary to reflect new information from wells and refine previously published interpretations.

CO₂ storage

CO₂ storage capacity in the SNS area has been estimated at 15 Gt (representing almost one fifth of the P50 estimate of total 78 Gt on the UKCS), (Bentham *et al.* 2014). If proven, this would equate to c.50 years of CO₂ storage for UK emissions (302.8 Mt in 2023) in the SNS alone. To date, a total of 18 carbon storage licences have been issued in the SNS area (of a total 27 UK-wide) and the first project is expected to become operational in 2028 (DESNZ, 2024). With up to 100 sites capable of storing 1.6 GtCO₂ needed on UKCS to meet 2050 net zero targets, further CCS licence rounds are anticipated in the coming years (NSTA, 2025a). This is required to feed the funnel of projects and stimulate scalable economic models for CCS through import and storage, while allowing for the possibility that some sites will not progress.

At a high level, many potential sites in the SNS appear to meet the criteria for CO₂ storage (e.g. Bentham *et al.* 2014; Hamilton *et al.* 2022; Underhill *et al.* 2023). Ideal conditions include: 1) A large, well-connected reservoir with sufficient permeability and porosity to allow efficient injection rates and the capacity to store large volumes of CO₂; 2) A durable seal to trap and prevent migration and leakage of CO₂ back to the atmosphere; and 3) Pressure and temperature conditions which will ultimately allow storage of a greater volume of CO₂ in its dense or supercritical phase than in its gaseous phase (>31°C and >74 bar), which given the geothermal gradient in the basin corresponds to depths below c.800 m (e.g. Ringrose, 2020).

Highly depleted gas fields, particularly those in areas of extensive and dominantly aeolian Leman Sandstone Formation (Fig.12a), form partially closed or closed (hydraulically isolated) sites that are sealed by evaporite deposits of the Zechstein Group (Fig.12b). Evidence for gas having been trapped for millions of years and in some cases with naturally occurring CO₂ (e.g. Underhill *et al.* 2009), underlines the potential for secure storage in many of these deeply buried fields.

Where post-depositional salt movement (halokinesis) has occurred in the basin (Fig.12b; Underhill, 2009), numerous structural closures in the Bunter Sandstone now provide attractive saline aquifer storage potential (Fig.12c). However, in some areas Bunter closures are close to or subcrop just below the seabed (Figs.11 and 13a). Consequently, MMV techniques may need to be applied across the wider regional aquifer to monitor pressure and migration of fluids and identify any geological leakage pathways to the seabed (e.g. Gibson-Poole *et al.* 2024b).

Hydrogen storage

Hydrogen is an energy vector that has been proposed as an alternative to natural gas in hard to decarbonise sectors, with storage required to meet times of peak demand (Johnson *et al.* 2025). Subsurface storage in hermetically sealed salt caverns is a proven technology with several small onshore salt caverns used for storage of natural gas located in the UK, e.g. in Permian and Triassic salt deposits in East Yorkshire and Cheshire (Williams *et al.* 2022; locations also shown on Fig.12b). Salt caverns currently store hydrogen for chemical processes in Teesside (Saltholme) while others are currently being explored to aid industrial decarbonisation in East Yorkshire (e.g. Aldbrough Hydrogen, 2025) and Cheshire (e.g. the Salinae Hydrogen Storage Project near Warmingham; Uniper Energy, 2025). Larger scale hydrogen storage is already operational in the USA (Clemens, Spindletop and Moss Bluff salt domes) and is planned at many additional sites around the world (see Zivar *et al.* 2021).

Optimal conditions for hydrogen storage in salt caverns require a thick interval of homogenous halite (rock salt) at deeper than 500-1000m to efficiently operate at high pressure, and shallower than 2000m to prevent deformation of the cavern through salt creep (Marín *et al.* 2023; Van Gessel *et al.* 2022). Thick layers of evaporitic sequences are present in five depositional cycles of the Zechstein Group (Z1-Z5) across the UK sector of SNS (Peryt *et al.* 2010). The most extensive of which, Z2 is shown in Fig.12b and used here to indicate potential storage areas. These include salt pillows and diapirs formed due to salt mobilisation in the central parts of the basin and thick beds of undeformed salt closer to the basin margin. Several recent assessments suggest that projected UK storage requirements of 3.2 TWh by 2030 (Hydrogen UK, 2022) could be met with development of offshore salt caverns in the North Sea (e.g. Barnett *et al.* 2024; Caglayan *et al.* 2020). However, there are currently no offshore hydrogen storage licences on the UKCS.

Other examples of hydrogen storage include historic storage of town gas (40-60% hydrogen) in saline aquifers and salt caverns across Europe in the 20th Century (Kruck *et al.* 2013). By contrast, large-scale storage of pure hydrogen in porous formations is an emerging technology. In 2025, the first pure hydrogen storage and production cycle using a depleted gas reservoir was reported from the Rubensdorf-Gampern site in Austria (Renewables and Gas Austria, 2025), paving the way for further projects (EUH2STARS, 2025). The potential for re-purposing depleted gas fields in the UK has also been recognised (e.g. offshore,

Peacock *et al.* 2022) although some proposed sites have not stood up to geological scrutiny (e.g. onshore, Cousland; Butler & Underhill, 2024).

The pace of hydrogen uptake over the coming decades introduces uncertainty in demand for storage sites and despite potential differences in selection criteria, could lead to competition for pore space with other subsurface storage industries. Moreover, the varied hydrogen production processes (e.g. Incer-Valverde *et al.* 2023) mean that synergies with CCS (to store CO₂ emissions from blue hydrogen production using natural gas) and offshore wind (to power green hydrogen production) will be important factors in any site selection process.

Natural gas

Natural gas is heavily relied upon in the UK for heating buildings (including 73% of households or c.21 million homes, UK Parliament, 2024). Used for around 30% of the UK's annual electricity generation (DESNZ, 2025f), gas can contribute over half the country's needs on occasion and thus, plays an essential role in providing baseload power (the minimum electricity required to supply and stabilise the grid). Dispatchable gas power enables adjustment of output to match fluctuations in demand and provide a reliable supply at times when renewables are not generating. Although the intent remains to move away from the current reliance on gas, it is generally accepted that there will still be a need for it in 2050 and beyond (Committee for Climate Change, 2020; DESNZ, 2025g), through domestic supplies or imports.

Although North Sea hydrocarbon production is in decline (Underhill & Richardson, 2022; Underhill *et al.* 2023), a large part of the southern ENS remains licenced for gas exploration and production (Fig.6a). New discoveries such as Selene and Pensacola have recently been made (e.g. Cafferkey & Dack, 2024) and numerous other leads and prospects provide future opportunities for domestic production of gas.

NSTA data (2025b) suggests there are 88 undeveloped discoveries in the ENS. In addition, there are remaining reserves in stranded gas fields (most notably, due to closure of the Caister-Murdoch-Schooner (CMS) pipeline and Theddlethorpe gas terminal in 2018). While incremental, continued production and development of some of the larger prospects in the area (e.g. Table 3) could contribute to short-term supply and energy security. Recognising this need, the 33rd UKCS offshore licensing round, (launched under a previous government) saw new licences awarded in 2024.

Under the current government's plan for the North Sea's clean energy future outlined in the North Sea Future Plan (DESNZ, 2025g), existing oil and gas fields will be allowed to continue production, but it has been stated there will be no new licensing for exploration. However, a report published during the consultation period highlighted the detrimental climate, environmental sustainability, energy security and socio-economic implications of this approach (Underhill, 2025). A slight softening of the government's stance now means that tiebacks of discoveries adjacent to existing infrastructure will be allowed through the introduction of Transitional Energy Certificates (TECs). Where fields are no longer producing oil and gas, there are opportunities to support the energy transition by repurposing them for storage of gas, CO₂ or hydrogen.

There is just over 3 bcm of gas storage in the UK, equating to around 12 days of average winter gas demand (DESNZ, 2025a, Chapter 4). Increased gas storage capacity could

mitigate volatility in gas price and demand and provide energy security and reliability when weather conditions reduce renewable energy supply. The UK's largest storage site is the depleted gas field 'Rough' in the SNS Leman Sandstone reservoir (Stuart, 1991). Providing half of the UK's storage capacity and with the potential to increase capacity or switch to hydrogen storage, the future of Rough is uncertain due to the investment required to redevelop the site (Centrica, 2025). Other examples of gas storage in the UK include onshore sites at Hatfield Moors (Ward *et al.* 2003) and Humbly Grove (Gluyas *et al.* 2020) and salt caverns in Eastern England and Cheshire (Evans & Holloway, 2009).

With low levels of UK-based production and limited subsurface storage, the UK's strong reliance on imports increases vulnerability to geopolitical tensions. In 2024, net imports as a proportion of primary supply were 43.8% (DESNZ, 2025a, Chapter 1). The largest import source is Norway, with one pipeline (Langeled) providing 52% of all gas imported to the UK in 2024 (DESNZ, 2025f). The reliance on the Langeled pipeline, which serves the terminal at Easington, signifies a single point of failure of critical national infrastructure that would result in substantial disruption to UK gas supplies and energy security.

Other use of the subsurface

Structural deformation due to salt mobility (halokinesis) and a regional tilt imparted in the Cenozoic (e.g. Brackenridge *et al.* 2020), has brought rocks of different ages and lithologies to subcrop beneath a veneer of Quaternary sediments at the seabed (Fig.13a). One consequence of the down-to-the-east tilt is shallow access to Permian age (Z3) salt-bearing strata in Boulby mine. The facility extends beneath the seabed off the North Yorkshire coast (location indicated on Fig.6a). The mine supplies organic fertilisers to the global market, around half of the UK's rock salt requirements for road de-icing and hosts an underground laboratory for scientific research (De Angelis, 2017).

Further south along the coast of eastern England, sediments with potential for geological storage of radioactive waste have been identified in the vicinity of the now demolished Theddlethorpe gas terminal (RWM, 2021). However, due to lack of social acceptance, the local council withdrew its membership of the community partnership formed to explore the option further (Lincolnshire.gov.uk, 2025; NWS, 2025).

Potential for ageing hydrocarbon fields to be repurposed as geothermal resources has also been proposed (Auld *et al.* 2014, Gluyas *et al.* 2018). Sites associated with high rates of co-produced water (with oil production), in areas with a high geothermal gradient are preferable. As such, application is unlikely in the ENS. In an assessment of the Magnus oil field in the Northern North Sea, results indicate that geothermal heat and power could reduce emissions from existing production and contribute to powering future carbon storage operations (NZTC, 2024).

Saline aquifers and salt caverns can also offer potential for compressed air energy storage (CAES). The process uses excess electricity to compress air that can be stored and later released to drive a turbine and generate electricity when needed (e.g. Huntorf, Germany, Crotagino *et al.* 2001). Recent studies have identified potential for CAES in the UK in salt caverns (Evans *et al.* 2021) and offshore in saline aquifers (Mouli-Castillo *et al.* 2019). In addition to the high costs involved, additional challenges include the low energy density of compressed air and lack of efficiency due to energy being lost as heat. However, as a large-

scale energy storage solution, CAES also offers potential synergies with renewable energy and is a growing area of research (Dooner & Wang, 2020).

Cross Sectoral review

To use the subsurface effectively requires access to the seabed, water column and airspace. In turn, this demands knowledge of why and how it has been, is currently (Fig.6b-d), and will be utilised by all stakeholders. With characteristics of the seabed being such an important control on the distribution of many offshore activities, Fig.13a-c summarises its varied geological and geomorphological features. These features impact the position of infrastructure including routing of cables and pipelines, control where sand and gravel extraction can occur, constrain the location of shipping routes, provide important habitats for marine life and influence the location of productive fishing grounds.

Using publicly available information, areas of importance for subsurface activities, offshore wind, fishing, marine environment and biodiversity, shipping and marine aggregates are identified (Figs.14-19). The focus is on human activity. In each example, presence of other stakeholders with a claim or interest in the same area (based on interactions in Fig.9), including any spatial requirement identified in Table 1a-d, are used to illustrate the cumulative spatial pressures relevant to each sector. With the aim to identify areas of potential conflict, activities generally considered as compatible (passive or minimal interference) are not included. Areas of planned and consented offshore wind (i.e. where no infrastructure is present yet) are not included in the layer count and are shown as outlined areas. This is to illustrate the extent of existing spatial pressure arising from other sectors with a claim or interest in these areas.

For completeness, other offshore use is also described including infrastructure, recreation, airspace (see Figs.6b-d) and a summary of historical activity (Fig. 20), all of which can impact accessibility and introduce risk to existing and future activity. Due to the focus on spatial practicalities of offshore planning, economic factors are not included in this review.

Recognising that without solutions there will be winners and losers in the energy transition, the series of summary maps provide: 1.) a clear indication of areas where co-location solutions will be required to minimise or mitigate the impact of other users if the status quo remains; and 2.) identification of areas where protection or preservation for future activity could be considered in the offshore planning process if it is deemed that co-location is not feasible.

Subsurface activities

Areas with potential for offshore subsurface storage and future hydrocarbon extraction include currently producing and depleted fields, undeveloped discoveries and stranded gas fields, saline aquifers, salt structures and areas of thick undeformed salt and sediment (Fig.12a-c and combined in Fig.14a). The figures indicate the high-level distribution of subsurface resources in the ENS which can be considered to have a fixed spatial location. However, it should not be assumed that all sites will be suitable as there are many geological and engineering factors that can rule out their use.

Geologically, the extent of a potential subsurface storage unit is controlled by the basin structure at the time of deposition. Variation in the type of sediment deposited, combined

with subsequent processes spanning hundreds of millions of years such as its subsidence history, post-depositional tectonism, burial diagenesis, faulting, reactivation, erosion, and mobilisation of salt, constrain the availability and viability of subsurface resources.

For hydrocarbon prospectivity, all the elements of a petroleum system must be in place. This includes the occurrence and maturation of a source rock to generate hydrocarbons, presence of porous reservoir rocks, a trap sealed by a strong caprock, migration of the hydrocarbons into it and long-term preservation of the system. Timing of these processes is essential, and the nature of hydrocarbon exploration carries high risk.

Other geological constraints including geometry, structural, stratigraphic, fault compartmentalisation, and aquifer character (e.g. pressure, temperature, salinity, connectivity) can impact storage efficiency (e.g. capacity, injectivity), (Ambrose *et al.* 2008; Bachu 2015; Bump *et al.* 2024). In salt caverns, presence of mixed lithology (heterogeneity) can impact cavern formation and integrity (e.g. Marin *et al.* 2023). While these geological factors can impact the viability of some sites, a primary concern for subsurface storage centres around the presence of legacy wells (Torsæter *et al.* 2024). Site evaluation must address the risk of leakage associated with the geology (e.g. along a fault or through the variation in seal lithology), or a well (mechanical or corrosion and completion configuration) that may result in development of permeable pathways through the subsurface back to the surface (e.g. Watson & Bachu, 2009).

Risk of leakage from legacy wells is associated with wellbore completion and abandonment (i.e. plug position, cement type and quality), (e.g. Gasda *et al.* 2004, 2020). Since 1964, over 2800 wells have been drilled in the ENS, of which 59% are associated with a field development. In the UK, wells drilled post-1996 are subject to the Offshore Installations and Wells (Design and Construction, etc.) Regulations (1996) introduced to aid long-term integrity. The impact of aging legacy wells on subsurface storage projects is uncertain. Lack of well integrity in just one instance can be enough to compromise a project and result in loss of potential storage capacity. Due to this concern and prior to the start of injection, the UK CCS regulator (NSTA) require a well integrity assessment for every well within the storage site and completion of any mitigation measures to ensure storage security. This is to '*demonstrate that under the proposed condition of use of the storage site, there is no significant risk of leakage*' (NSTA, 2023a). For hydrogen storage in porous formations, the risk of leakage may be much higher due its small molecular size and its potential ability to diffuse easily through rocks and interfaces with well completion materials (e.g. van Gessel *et al.* 2022).

While admittedly challenging, compatibility between subsurface activities could be possible at different stratigraphic levels if drilling through an overlying store or field can be avoided. In the same geological interval, regional pressurisation of an aquifer can potentially limit the storage capacity of multiple sites (e.g. for carbon storage in the Bunter Sandstone, Abel *et al.* 2024). In contrast, where there is little to no aquifer connectivity, for example in highly depleted Rotliegend Group reservoirs, sites may be utilised as stand-alone storage solutions for CO₂, natural gas or hydrogen storage.

As there is no longer any gas production from the Bunter Sandstone, interactions due to simultaneous production and storage in this geological interval are likely to be intentional and associated with water extraction measures to manage pressure and increase storage

capacity. In other offshore areas, pressure communication between adjacent and different subsurface projects (oil/gas production and carbon storage), can introduce complexity. While technically possible, solutions will require collaboration between subsurface operators to manage multiple developments in the same geological unit. Where there is interest in the same geographical and geological interval, sequencing of activity can enable depletion of a field prior to its re-use for storage.

Where viable, use of the subsurface is generally compatible, or able to co-exist with most offshore activities (Fig.9). With a small spatial footprint at the surface and seabed, co-location solutions are possible if the spatial requirements for infrastructure are considered at the planning stage. However, through uncoordinated allocation of offshore wind leases above potential storage sites, it has become apparent that for both wind and carbon storage to use the same area, technical solutions must be sought that allow co-location and enable access (TCE, 2023).

Use of the subsurface for storage requires access to the marine space and seabed from the pre-injection to post-closure phases of a project. For CO₂ storage, this can take place over approximately a 50-year period (e.g. MMV plan for Endurance, BP, 2021). The key areas of concern are associated with rig access (drilling, workovers, intervention of legacy wells, decommissioning); space for MMV of the storage site; and operational access (safe transport corridors) for routine operation and maintenance works. Repeat towed streamer seismic surveys are the most well-known and mature technique for monitoring a CO₂ storage site (e.g. Furre *et al.* 2017) but are not practical in close proximity to permanent seabed installations. In these areas, access issues include risk of collision, snagging and loss of expensive equipment resulting in significant implications for marine insurance.

A feasible and alternative method of seismic acquisition uses Ocean Bottom Nodes (OBN) which are placed on the seabed. Acquisition using OBN technology inside a wind farm is technically possible but is currently perceived as prohibitively expensive and therefore unfavourable (e.g. NSTA, 2022a). The site-specific variation in surface and subsurface conditions means there is no one size fits all MMV solution. Other monitoring technologies are at different stages of development, are yet to be proven effective, provide information at different resolution and have a range of associated costs. As a result, projects unable to include seismic monitoring may be delayed further risking the loss of possible storage opportunities.

Spatial pressure from other sectors that could impact development of subsurface storage sites and undeveloped hydrocarbon fields (from Fig.9) is shown in Fig.14b. While much of the storage potential in the ENS is defined by structural closures, it is possible that infrastructure associated with development may fall outside of the equivalent area at the seabed. This could include sites where down-dip injection is planned to maximise migration assisted storage or there is a need for pressure management of the aquifer through water production. Therefore, in this scenario, areas currently licenced are also included in the footprint of potential activity. Existing offshore wind areas have been treated as a hard constraint as these areas are not likely to be easily accessible due to the spatial requirements needed for subsurface storage and oil and gas field operations. Overlaps with oil and gas licences and infrastructure may reduce as fields cease production and infrastructure is decommissioned or re-purposed. However, the extent of planned offshore

wind indicates the importance of finding solutions that prevent the closure of marine areas to future subsurface use for storage.

Offshore wind

To date, all operational wind farms in the study area are located in areas with favourable geotechnical conditions to enable deployment of monopile (fixed) foundations. In anticipation of scaling up fixed and floating offshore wind developments, a characterisation of Key Resource Areas (KRAs) was undertaken by Everose (2020) for TCE. The outcomes from their study were used to identify areas with suitability for deployment of different wind technology groups (based on foundation system) depending on site specific conditions, including depth, thickness of sediment cover and strength of the underlying bedrock. Fig.15a is a simplified map of their results showing areas with suitability for fixed, floating or both types of offshore wind which suggests that there are engineering solutions available to enable deployment almost anywhere in the ENS area.

There are currently 29 wind farms operational or under construction in the ENS and a further 15 are consented and planned or paused (e.g. Hornsea-4). Rapid completion of all currently consented and planned developments in the region would mean 66% of the UK's 2030 offshore wind generation target of 50 GW, could be met in this area alone (based on data from TCE, 2025b, p.10 & 29). This can be estimated to save around 60 Mt CO₂ emissions per year (compared to equivalent gas-fired electricity generation).

At present, there are approximately 1640 operational turbines in the ENS with c.1900 new turbines planned in the area (based on data available from developer websites). As the power output of a wind farm is determined by turbine design and layout (power density), the area ultimately occupied can be smaller than the initial lease areas (e.g. Outer Dowsing Offshore Wind, 2023, para. 4.1.10). Assuming installation of larger 10-14 MW turbines with a power density of 5 MW/km² (e.g. Bulder *et al.* 2018), the spatial footprint of fixed offshore wind installed in the ENS could be expected to increase by around 5000km². This is the equivalent of 62% of the total area currently categorised as under construction, consented or planned. Further growth of the sector is also expected as floating wind technology allows expansion into deeper waters and new areas are opened for future leasing rounds (e.g. the North East area of opportunity for future wind, TCE, 2025c).

Activities and interactions (from Fig.9) in areas suitable for offshore wind indicates the current lack of compatibility with subsurface use (Fig.15b). This represents a present-day scenario and reflects the current marine plan policies (2014) that projects within areas of existing oil and gas production should not be authorised unless compatibility can be demonstrated (Policy OG1), and the preference that a development will not prevent carbon storage (Policy CCS1). In this scenario, current gas production licences together with licenced CCS areas are included as hard constraints alongside existing use/activity associated with seabed infrastructure, aggregates extraction sites and shipping routes.

With competing claims to airspace, the water column, the seabed and the potential to restrict or prevent access to the subsurface beneath, offshore wind results in the highest number of conflicts with other sectors (Fig.15b). The numerous overlaps also highlight the importance of recognising and integrating the complex links that exist between both human and non-human offshore activity prior to designating further areas for offshore wind.

Environment and biodiversity

A Marine Protected Area (MPA) is a broad term used for sites designated to protect species, habitats, ecological processes and geological or geomorphological features of national and European importance (JNCC, 2025a). Concerns over the impact of human activities on the oceans include loss of biodiversity and weakening of the oceans ability to resist, recover and adapt to climate change (Depledge, 2024; Halpern *et al.* 2025; OSPAR Commission, 2023). With aims to 'halt and reverse' biodiversity loss, the Global Ocean Alliance (GOA), targets the protection of 30% of the global marine environment by 2030 through a network of MPAs and other conservation measures (HM Government, 2025a).

There are currently 377 MPAs covering 38% of UK waters, of which 181 (40%) are in England (JNCC, 2025b). In the ENS, 53% of the area is currently designated as an MPA (Fig.16a). Activities taking place within MPA's must further specific conservation objectives or take place in a manner that least hinders achievement of the MPA objectives such as when there is an overriding public interest (DEFRA, 2024a). The most restrictive areas for marine activities are Highly Protected Marine Areas (HPMAs) introduced to aid ocean recovery through whole-site protection. In these areas, extractive, destructive and depositional activities including commercial and recreational fishing, dredging, construction and anchoring are prohibited (DEFRA, 2023). The first HPMAs in English waters were designated in July 2023 including NE of Farnes Deep in the northern part of the ENS and further sites are being explored for future designation.

Use of the ENS by the silent stakeholders is summarised in Table 2 and included in Fig.16a. As an important spawning and nursery ground for North Sea fish stocks, the shallow, biodiverse waters of the ENS have played a crucial role in food web stability, which remains essential to the future of the UK fishing industry and food security. Spatial identification of fish habitats (Ellis *et al.* 2012) indicates that 77% of the ENS area contains spawning and nursery grounds for at least three species. The presence of sandbanks and biogenic reefs (e.g. Norfolk sandbanks and Saturn reef, see Fig.13c and Fig.16a) provide habitats for a diverse range of benthic species, many of which are protected within MPAs to allow conservation of their structure and function (JNCC, 2010).

Due to the risk of damage resulting from bottom trawling, some of the most sensitive seabed areas are also subject to fishing restrictions (see Fig.17b). Other fishing restrictions include a ban on commercial fishing of sandeel within English waters of ICES Area 4 (North Sea) (DEFRA, 2024b) in response to concerns around decline of the seabird population in the UK (JNCC, 2023; Stanbury *et al.* 2024). Data available from WWT Consulting (2013) for 22 species of birds located in Special Protection Areas (SPA) and Sites of Special Scientific Interest (SSSI) indicates that 85% of the ENS area provides foraging grounds for more than three species (area shown in Fig.16a).

The implications for conservation and biodiversity mean siting of any offshore development is subject to Environmental Impact Assessment (EIA) and Habitat Regulations Assessment (HRA) which, at least in the early planning stage, implies its priority status (Fig.9). However, the specific objectives of a designated MPA may not necessarily conflict with a development which, in the case of offshore wind, resulted in the UK Offshore Energy Strategic Environmental Assessment to recommend that '*preference should be given to locating wind farms in such areas to mitigate potential spatial conflict with other users*' (DECC, 2009). In

other sectors, much of the legacy infrastructure was in place prior to the onset of offshore MPA designations in the UK in 1999 and 2013 (for a history of MPAs in the UK see Marine Conservation Society, 2025).

Development activity can be given approval if evidence can be provided that any impacts are short lived, e.g. sand wave clearance for cables (ABPmer, 2018). Where it is not possible to 'conclude no adverse effect or that the proposal does not hinder the conservation objectives of the MPA' (JNCC, 2019), the case for overriding public interest can allow developments be permitted with strategic compensatory measures in place, such as artificial bird colonies (see Christensen-Dalsgaard *et al.* 2019; McGregor *et al.* 2022) and extension of the MPA network (adjacent to an area or within the same region) (DEFRA, 2025a). However, the potential for new structures to impede seismic monitoring if located within the area of a CCS licence highlights the importance of wider consultation with the subsurface sector.

Areas where the presence of current offshore activities may impact environment and biodiversity aims are shown in (Fig.16b). Spatial pressure is currently highest in the shallower southern ENS and is primarily associated with infrastructure and existing oil and gas activity, however, the largest extent of overlap occurs with the fishing industry.

Fishing

Commercial fishing effort based on Vessel Monitoring System (VMS) data indicates that bottom towed gear, primarily beam trawls targeting flatfish (sole, plaice) and shellfish are the most common gear types used in shallow areas of the ENS (a sub area of the Greater North Sea and ICES statistical rectangles 4.b and 4.c, see ICES, 2022). Shellfish form the bulk of UK fishing port landings in the SNS (MMO, 2024a) and a small shellfish aquaculture industry operates in intertidal bays along the eastern coast of England (see Fig. 6c). Aquaculture is a growing industry in the UK due to an increased demand for seafood and its importance for local, regional and global food security (Black & Hughes, 2017). Although there is limited spatial data available for the current aquaculture industry in England, several areas with suitability for future shellfish and seaweed farming have been identified in the ENS (MMO, 2013a).

Fish is a low carbon protein source and fishing activity supports the social, cultural and economic outcomes in many coastal communities (MMO, 2024b; Reed *et al.* 2013). In recognition of the different types of fishing gear and variation in levels of activity, data representing fishing effort (2019-2022) was normalised to indicate areas important to fishing in the ENS (Fig.17a, also see Supplementary material: Appendix C). Using this method, 36% of the total ENS area can be classed as high activity fishing grounds (where 75% of activity for at least one type of gear occurs). It is important to note that the data this analysis is based on is limited to vessels over 12m in length. With 79% of the UK fleet in 2022 under 10m (MMO, 2024a), fishing activity is likely to be underestimated, particularly in inshore areas.

Inshore fishing activity typically refers to smaller (under 10m long) vessels undertaking activity within 12nm of the coast. Its existence is under pressure due to a recent UK-EU deal (2025) to allow international vessels to fish within the 6 to 12nm zone and the UK's share of Total Allowable Catch (TAC) which allocates just 2% to the under 10m sector (Anbleyth-Evans & Williams, 2018). In future, planned legislation will require vessels under 12m in

English waters to install an inshore VMS device which will provide further insight into the fishing activities of smaller vessels (MMO, 2025b). This data will be vital for addressing the need for access and inclusion of fishing in future offshore spatial planning as other sectors increase their activity in inshore areas.

The Fisheries Act (2020) states that UK boats can access any part of UK waters and includes objectives for sustainable management balancing social and economic benefits while preventing over exploitation of marine stocks. However, there are areas, shown on Fig.17b, where MMO and IFCA's byelaws restrict or prohibit use of certain types of gear (permanent or seasonal) to balance the needs of the fishing industry with protection of the marine environment (Association of IFCA, 2024; MMO, 2023a; Seafish, 2024). Furthermore, despite fishing being permitted within offshore wind farms in the UK, the risks arising from snagging cables and associated safety, legal and insurance concerns have led to a reluctance to fish within them (Dunkley & Solandt, 2022; Gray *et al.* 2016; Haggert *et al.* 2020; Szostek *et al.* 2025).

Areas where the presence of other stakeholders can impact fishing activity are highlighted in Fig.17b. The most intense spatial pressure occurs in the southeastern area where busy shipping lanes cross an area of high fishing effort. Elsewhere in the ENS, increased spatial pressure results from offshore wind developments and their associated infrastructure. Interestingly, where offshore wind was operational during the same period reflected in the fishing effort data, there is some evidence that fishing has begun to be excluded from offshore wind farms (e.g. SE part of the ENS, Fig.17a). It should be emphasised that the dataset on which Fig.17a is based, predates construction and operational phases of some of the larger, more recent windfarms and as such, does not yet capture any impact of these developments on fishing effort in those areas.

Due to its mobile nature, fishing is technically feasible and legally permissible everywhere except designated no-go areas which includes HPMA's. It is restricted or discouraged close to certain critical infrastructure (ESCA, 2022; KIS-ORCA, 2025a). Co-location solutions everywhere else can in theory, enable continued access to fishing grounds. Environmental and safety reasons can mean fishing is given lowest priority where there are potential interactions with other sectors (e.g. with marine protection, shipping, cables and pipelines; Fig.9). Additionally, there is a need to consider the wider and complex links to environment and biodiversity. This, alongside the impact of encroachment of other sectors, reveals the multifaceted challenges facing the future of the inshore and offshore fishing industry as the ENS is utilised for the energy transition.

Marine Aggregates

The construction industry extracts marine (sand and gravel) aggregates for building (e.g. houses, nuclear power stations), transport infrastructure (e.g. bridges, ferry terminals and airports), port development and coastal and flood defence projects with its primary use in manufacture of concrete (MPA, 2020; TCE, 2024a). Contributing to large supply chains essential to the economy and quality of life in the UK, marine aggregates provide around 20% of Great Britain's sand and gravel demand, approximately half of which is extracted from the ENS area (TCE & BMAPA, 2025). In 2024, 9 Mt was extracted from the Humber, East Coast and Thames regions from 78km² equating to just 9-18% of the total area licenced in each region (TCE & BPMPA, 2025). Although the current spatial footprint of

aggregate extraction is relatively small, future scenarios out to 2035 indicate an increase in demand for marine aggregates due to long term supply pressures associated with land-won sand and gravel (MPA, 2022).

Variation in offshore seabed sediments in the wider ENS are shown in Fig.13b together with the location of 47 Production Agreement areas targeting extraction of sand and gravel and a further eight Exploration and Option areas marked for potential future production. The most prospective areas lie north of the last glacial maximum (marked on Fig.13c) and off the coast of East Anglia and in the Outer Thames Estuary. Gravel resources in these areas result from deposition in ancient river systems whereas further north, glacial outwash and moraines associated with the last major ice age provide the gravel resources in the Humber area (Bide *et al.* 2011; BMAPA & TCE, 2015). Sand resources result from modern reworking of sediment into sand banks and sand waves. Composition and grading determine suitability as construction aggregates (Highley *et al.* 2007) and deposit thickness of >1m is required for economic extraction (Bide *et al.* 2016). With maximum depths for marine aggregate extraction between 30 to 50m at the current level of technology (WYCA, 2022), activity is limited to the shallower areas of the ENS.

The distribution of mixed sand and gravel deposits from Fig.13b with areas deeper than 50m removed provides a high-level indication of aggregate resource areas (Fig.18a). Work undertaken by the British Geological Survey (BGS) further refines distribution of potential resource areas, noting that deposits in the Humber region can be unpredictable (Bide *et al.* 2011). The BGS defined area of optimal resource (2011) is shown on Fig.13b. However, as recent aggregates exploration and option areas have since been agreed outside of this area, it has not been used to limit the region containing potential resource. In areas where prospective areas are identified, initial six-year Exploration and Option Agreements are awarded from TCE allowing detailed surveying to establish presence of a commercial resource. If proven, a licence is then required from the MMO together with a production agreement from TCE for commercial rights to the area for a term of up to 30 years (TCE, 2024a).

The number of stakeholders with competing interests in areas with potential aggregate resources are shown in Fig.18b. Despite its destructive nature, extraction from within MPAs can be permissible subject to EIA approval of individual site features and conservation objectives. This can include requirements for seasonal restrictions on operational activity to minimise impact of sediment plumes on seabed habitats (BMAPA & TCE, 2017).

Due to its inherent lack of compatibility with other sectors (Fig.9), combined with the potential to restrict access (albeit in small areas) for extended periods of time, efforts are taken to minimise the licence footprint and ensure navigational safety is not compromised (BMAPA & TCE, 2017). In an area with a high number of overlapping claims and interests from other sectors, early identification and evaluation of further resource areas will be essential for sustainable management of future aggregates supply.

Shipping

Being an island and due to its strategic location, the UK is one of the largest trading nations and the North Sea region has become one of the busiest shipping areas in the world (Nilsson *et al.* 2018). Major shipping lanes provide access to ports across Europe and transit routes

allow access to and from the Atlantic Ocean and Baltic Sea. Several ports face the ENS (shown on Fig.19a) including Teesport, Port of Tyne and the UK's busiest port complex located in the Humber Estuary which handles 17% of UK trade and over 40,000 ship movements per year (Humber Freeport, 2024).

Shipping activity is summarised in Fig.19a indicating the distribution of routes taken through the ENS. Main shipping routes are indicated by at least one route per day for any vessel (as defined in Table 1c). Areas with at least one route per week are included to demonstrate wider use of the ENS for the transit of fishing and other vessels, e.g. operational support vessels for offshore wind farms and gas fields. The main routes that are taken by larger tanker, cargo and passenger vessels are used to illustrate presence of restrictions due to highly variable seabed morphology. A 20m depth contour highlights large, kilometre-scale linear sandbanks, e.g. the Norfolk Banks (Fig.13c), (Collins *et al.* 1995; Cooper *et al.* 2008) which influence shipping routes due to the risk of grounding in shallow waters. In the most congested areas, ships' routing measures have been established by the International Maritime Organisation (IMO) to improve safety of navigation at sea. Several are present in the ENS (Fig.19a) and include deep water routes and traffic separation schemes to reduce risk of collisions and groundings in line with the SOLAS convention (Ch. 5, 2002).

The presence of sectors that overlap areas of current shipping activity are shown on Fig.19b. Most sectors are compatible with shipping provided they do not interfere with safe navigation. In almost all areas with more than one shipping route per day, space is currently shared with at least one other sector. The most common overlap occurs with fishing, which although transitory, may increase in frequency as it is displaced due to increasing pressure from MPA restrictions and exclusion from offshore wind developments.

Infrastructure

The cables and pipelines that cross the seabed (Fig.6b) form a network of communications and energy connections vital to everyday life in the UK. Infrastructure in the ENS area includes electricity interconnectors and pipelines linking the UK with Europe and thousands of kilometres of telecommunications cables. A network of domestic gas pipelines extends across the ENS connecting wellheads and platforms associated with producing gas fields to onshore terminals at Teesside, Easington and Bacton. The growing footprint of offshore wind adds turbines, intra-array cables and long cable corridors connecting wind farms to onshore terminals. With a large portion of renewable energy set to be generated in Scottish waters, major grid upgrades include plans to transfer power to areas of demand including large population centres in the south of England via high voltage direct electrical subsea cables (EGL1, 2024; EGL2, 2024; National Grid, 2024). Furthermore, five major new undersea energy links are planned to enable export and import of electricity with Europe, (Ofgem, 2024) increasing reliability of supply as energy systems become increasingly dependent on renewables.

The high density of strategic cable and pipeline infrastructure in the ENS currently results in overlap with all offshore sectors. It has a clear priority when interactions with other users are considered due to the need for prevention of damage (Fig.9). Co-location challenges to date have meant that protection measures are often necessary (e.g. cable and pipeline burial or rock placement, KIS-ORCA, 2025b) as around a third of global cable faults are caused by fishing activity and around a quarter by anchoring (Carter *et al.* 2009). While many users can

co-locate with the presence of this infrastructure, detailed planning is required to ensure compatibility at the site development scale due to spatial requirements or constraints such as those indicated in Table 1b (e.g. for safety and maintenance or presence of legacy infrastructure). Given their importance, geographic spread and growing presence on the seabed, challenges associated with planning around these vital arteries to and from the UK have major implications for future activity and national security.

Other infrastructure includes legacy oil and gas wells, resulting from hydrocarbon exploration, appraisal and development activity across the basin since the mid 1960's. Most of these wells (77%) are now abandoned and 60% are fully decommissioned with their casing strings removed below the seabed (based on data from NSTA, 2025b). Any equipment and remaining debris are also cleared, enabling restoration of the seabed to a natural state and any fishing activity in the area to resume (OEUK, 2022a).

Platforms associated with field developments are coming offline as production declines. The decommissioning of infrastructure forms a major component of the UK's hydrocarbon industry's activity, creating opportunities for the UK supply chain and employment. For instance, having produced 1.79 TCF, from the Shell/Esso side of the Indefatigable Field, five platforms were taken to a Tyne shipyard after production ceased in 2005 (Shell, 2014).

Leaving infrastructure in place within the maritime area is prohibited (Decision 98/3, OSPAR Commission, 1998) however, it is not always possible to remove the footings of large steel jackets (placed before 1999) or concrete installations. In this case, any remnant of an installation, pipeline or deposits that are left *in situ* and a danger to navigation are marked on Admiralty charts. Although post-decommissioning monitoring, maintenance and liability resides with the operator, safety zones around infrastructure (e.g. Table 1b) may only remain in place until decommissioning activity is completed (OPRED & BEIS, 2018).

It has been estimated that the SNS accounts for around £4.5bn of the c.£40bn cost of decommissioning upstream oil and gas infrastructure on the UKCS (NSTA, 2023b). With potential to reduce these costs and provide savings on subsurface storage projects, reserving and repurposing of infrastructure is considered a key enabler of the energy transition (NSTA, 2025d). As such, there are plans to reuse the 120km LOGGS gas pipeline from the former Theddlethorpe gas terminal for CO₂ transport offshore to the Viking CCS storage site, (Planning Inspectorate, 2024b; Viking CCS, 2025b).

Recreation

Marine recreation contributes to societal health and wellbeing, has a positive economic impact within coastal communities and can help promote conservation projects (DEFRA, 2019; Elliot *et al.* 2018). The area of recreational use indicated in Fig.6c includes unconstrained public use of the marine area for non-licensable (e.g. sailing, boating, diving) and licensable (e.g. angling) activities which typically take place within the 12 nautical mile limit. Use of the marine area for recreation has strong seasonal variation, the potential to take place over a wider area (MMO, 2014) and levels of activity could increase with warmer weather (Coles, 2020). Understanding the distribution of recreational activities therefore has implications for balancing access for recreation with the interests and claims of other sectors. This can include the need to prevent negative impact on conservation objectives (MMO, 2022) and locating cable and pipeline routes to connect to onshore sites with

minimum disruption. While short term construction activity is disruptive, the longer-term impacts of offshore wind infrastructure development are considered relatively minor and enabling co-location of activities can mitigate impacts on tourism and recreational use (Glasson *et al.* 2022).

Historic and other activities and uses

Additional items on the seabed result from a legacy of human activity, and while not necessarily associated with current use, they are summarised separately as their presence has implications for spatial planning at a local scale (Fig.20). Historic use includes:

- Unexploded ordnance (UXO) from World War I and II (including British and German minefields), military training exercises, and munitions disposal which have been discovered in all areas of the UK with a significant concentration in the SNS (OSPAR Commission, 2024).
- Over 5000 wrecks, obstructions and areas of foul ground present in the English North Sea area which have been categorised by varying levels of danger (UKHO, 2024).
- Areas of waste disposal associated with dumping of drill arisings associated with construction of wind infrastructure; seabed clearance associated with cable laying; dredging; and historic waste disposal areas with limited information available on the nature of any dumped materials (CEFAS, 2024).
- Piles of drill cuttings from oil and gas exploration discharged adjacent to drilling sites introducing different types of sediment to the sea floor and potentially impacting local environments and biodiversity (e.g. Breuer *et al.* 2004; Shell, 2017).
- Coal mining reporting areas indicating the known extent of coal mining activity where the risk of possible ground instability and potential mining hazards may require further assessment (Mining Remediation Authority, 2024).
- Other mining activities include potassium mineral (potash) mining at Boulby, where numerous shafts and tunnels extend under inshore regions of the North Sea (Paling, 2024).
- Dogger Bank, the final area of the larger 'Doggerland' landmass to be submerged beneath glacial melt and rising sea levels 6000 years ago (Veenstra, 1965; Gaffney & Thomson, 2007; Cotterill *et al.* 2017). The area is now of archaeological significance for advancing understanding of prehistoric life and impact of climate change on the landscape during a major period of sea level rise (Walker *et al.* 2022).

Aviation and military

Safe air operations and national security are of paramount importance. Around 7000 commercial, cargo, leisure and military aircraft use UK airspace every day (National Air Traffic Services (NATS), 2025a). Spatial claim for airspace relevant to planning offshore activity in the ENS primarily concerns military and helicopter operations (Fig.6d and Table 1d.) as commercial flying occurs at high altitude and within controlled airspace.

Challenges for aviation include the presence of wind turbines which can result in generation of unwanted returns within line of sight of Primary Surveillance Radar (PSR) and Ministry of Defence (MoD) radar systems (Civil Aviation Authority (CAA), CAP764, 2016). Special use airspace over the North Sea includes areas sometimes used as MoD Practice and Exercise

Areas (PEXAs) to maintain the UK's strategic defence capability. Military use takes priority and offshore developments should not inhibit the use of areas designated for this purpose (Defence Infrastructure Organisation, MoD, 2024). However, in the ENS, most activity in military PEXAs occurs above 5000ft (NATS, 2025b), high enough to avoid any significant impact with other sectors.

Other use of airspace includes helicopter transits (civilian transport to offshore installations) where Helicopter Main Routing Indicators (HMRI) are used to indicate the routes routinely flown. With no official airspace status, HMRI are mainly used to aid flight planning and provide a network of obstacle free pathways through uncontrolled airspace (see current AIP via NATS, 2025c). Consultation zones around offshore helicopter destinations are designated to maintain and ensure safety of operations, e.g. distance required for low visibility approach in poor weather conditions (CAA, CAP764, 2016).

In all areas important to civilian and military aviation, developments are subject to assessment, consultation and collaboration with the relevant stakeholders to determine any restrictions. In addition, operational and/or technical solutions are being sought to reduce the impact of offshore wind on air defence (DSA & DESNZ, 2024) and mitigate risks, e.g. installation of infill radar around wind farms to eliminate turbine radar interference (TERMA, 2024).

Notable challenges and inevitable consequences resulting from current overlaps

Loss of subsurface resources and storage potential

The high concentration of potential storage resources in the southern part of the ENS, underlines the need to assess individual sites for viability and acknowledge the requirements for their future access. This includes the need for a joined-up approach to managing the current overlap between oil and gas with carbon storage licences to ensure appropriate well abandonment can enable future storage projects.

With spatial requirements accounted for (see Table 1a-d), close turbine spacing, safety zones and layout of intra-array cables already restrict access to operational wind sites effectively closing these areas to many activities (Fig.9 & Fig.15b). For subsurface use, this means the location and spacing of offshore wind turbines have serious implications for simultaneous operations ("simops"), helicopter access ("heliops"), rig access, (length of towline, anchor chains and avoidance of underlying subsea cables) and MMV requirements. In the southern ENS the conflict is with fixed wind. The shift to floating wind technology in deeper waters of the northern ENS and other parts of the UK's EEZ could introduce additional challenges to accessing potential storage sites that lie beneath them.

For both carbon storage and offshore wind to play a part in the energy transition, their planning should not be undertaken in isolation. To demonstrate the impact, use of publicly available data to cross reference potential carbon storage sites (CO₂Stored, 2025) with the location of offshore wind sites (present and planned) indicates the potential loss of storage capacity in the ENS if access to subsurface sites is restricted (Fig.21 and Table 4). Where partial overlap exists, sites are included to account for the spatial requirements of monitoring the wider area. This could include many legacy wells within areas of planned offshore wind (Table 4). While recognising that not all sites will ultimately be viable for storage and that capacity estimates require updating, this high-level estimate indicates that development of all

currently planned wind farms in the ENS could compromise in excess of 1 Gt CO₂ of theoretical storage resource.

The slower pace of CCS deployment may also result in loss of access to the subsurface where offshore wind leases are subsequently granted. Uncertainty persists regarding cost and commercial models for CCS and significant investment is required in associated capture and transport infrastructure. In addition, wells need to be drilled. To meet the UK's 2030 target of injecting 20-30 MtCO₂/year, it can be estimated that 29-43 CO₂ injection wells would be required, assuming an average CO₂ injection rate for offshore wells of 0.7 Mtpa (see Ringrose & Meckel, 2019). By 2050, up to 250 CO₂ injection wells could be required to store the NSTA's target 75-175 MtCO₂/year in up to 100 sites. Achieving the 2030 target means that if sites were available, 7-11 CO₂ injection wells would be needed per year if drilling started in 2026 which is not technically unachievable. For perspective, 57 wells were drilled in the UKCS in 2023 including 16 exploration and appraisal wells. Of the 41 development wells drilled, three were in the SNS at an average cost of £7.8k per metre in (NSTA, 2024).

Despite recent government support aimed at getting more carbon storage sites into the track process, it seems highly likely that projects may be slower to reach final investment decisions than other energy transition technologies. At the end of 2024, DESNZ stated that *'its ambition to capture and store 20 to 30 million tonnes per year of CO₂ by 2030 is no longer achievable'* although revised targets have not yet been set (UK Parliament, 2025). With previous Carbon Budget Delivery plans found to be inadequate (Burnett & Stewart, 2025), a *'refreshed Carbon Budget delivery and Growth Plan'* was recently published placing less emphasis on the role of CCS (HM Government, 2025b). Incentivisation through the UK's Emissions Trading Scheme (ETS) and planned linkage with the EU ETS will therefore be a key driver in market creation for CCS and in wider plans to upscale and utilise the UK's subsurface storage potential (DESNZ, 2025h).

Human impact on marine biodiversity and ecosystems

The highest density of human activity in offshore waters of the UK occurs in the southern ENS due to its shallow seas and distribution of resources. In the East Inshore and Offshore region, over 78% of the area is designated as MPA of which, 50% is currently used by two or more human activities (Fig.16b). While many human activities have taken place in the marine environment over time, the recent pace of change and wider impact of cumulative effects are only just beginning to be recognised (e.g. Halpern *et al.* 2019).

Impact on marine ecosystem dynamics due to increased offshore activity and placement of infrastructure on the seabed in ecologically important areas may have consequences that are not yet fully understood (e.g. offshore wind, Watson *et al.* 2024). Habitat disturbance and loss, nutrient availability, impact on primary producers (the base of the food chain) and the knock-on effects at higher trophic levels (fish, mammals and birds) have implications for marine health, sustainability and management (OSPAR Commission, 2023). For instance, mixing and stratification may occur within the water column due to wind wake effects from offshore wind turbines (e.g. Christiansen *et al.* 2022), and modelling the predicted ecosystem response to wind wakes has indicated changes in spatial distribution of marine primary production (Daewel *et al.* 2023).

Other factors such as warming of marine waters due to climate change and intense commercial fishing for sandeel to supply the aquaculture industry (feed for farmed fish), have been linked to the decline in the UK's seabird population. A ban on fishing for sandeel is now in place to protect bird foraging areas (DEFRA, 2024b). Where wind farms could be built in key foraging areas or bird migration corridors, there are also concerns for increased numbers of bird fatalities. However, several in-house studies have challenged the assertion that blades kill birds (Vattenfall, 2023). High collision avoidance rates have also been observed in other areas with operational turbines (e.g. ORJIP, 2018; Vattenfall, 2025). While these examples attempt to address the uncertainty, wider consequences are exposed concerning habitat loss, the impact of which may vary between species and location.

The potential for habitat creation and increased biodiversity in offshore wind farms may offer support for their co-location with MPAs (e.g. Wilson & Elliott, 2009; Ashley *et al.* 2014). This potentially allows fulfilment of conservation objectives while limiting loss of ground to the fishing industry, although impact on biodiversity and ecosystems is uncertain and complex to predict. Furthermore, with the longer-term impact of climate change leading to warmer seas, MPAs may need to be relocated in future. With levels of human activity expected to rise, the demand for physical offshore space is likely to further threaten conservation objectives. Conversely, expansion of the MPA network and additional restrictions on activities within them may lead to unintended consequences as human activities are displaced into 'unprotected' marine areas.

Threats to the fishing industry and the need to adapt

Until recently, fishing activity has had relatively unconstrained access to the marine area. Yet, from a spatial perspective, it is becoming one of the most severely impacted sectors due to the increasing presence of offshore wind and marine protection measures. In the ENS, fishing activity is indicated in all areas where offshore wind is planned and consented (Fig.17a) and in 86% of areas currently designated as MPA. Where >75% of fishing activity for at least one gear type takes place (36% of the ENS based on data used in this study), 68% of this area would be impacted by the extent of consented and planned wind farm developments, and 40% currently overlaps with MPAs. In the ENS, inability to fish within currently designated MPAs and all planned and currently operational offshore wind farms would reduce access to total fishing grounds by 56%. In the same area, a recent proposal to ban destructive activity including bottom trawling from MPA's (DEFRA, 2025b) would reduce the area available to this gear type by 76%.

Exclusion on such a scale has major implications for access to key fishing grounds. In the ENS, the impact could be greatest in the East Inshore and Offshore region where over 86% of the current area fished hosts an interest or claim of at least three other sectors (Fig.17b). Without solutions to enable adoption of alternative technologies and co-location, the consequences of limiting offshore space for fishing include: displacement of fishing vessels into neighbouring areas, with concerns including compromised safety of navigation (e.g. in shipping lanes); competition amongst individual fishers and with other sectors; increased operating costs; reduced food security and, the resulting socio-economic impact on coastal communities (e.g. ABPmer, 2022; MMO, 2024).

In future, the deployment of floating wind in deeper water is likely to further limit the marine area available to the fishing sector due to the spread of mooring lines. For example, a plain

catenary system with a turbine to anchor distance of seven times a water depth of 80m (e.g. BVG Associates, 2023) could result in a total footprint of approximately 1km² per floating turbine, around 140 times the footprint of a single fixed turbine with a 50m safety zone.

Evolution and innovation in mooring systems (Edwards *et al.* 2023), shared anchoring (e.g. ORE Catapult/Arup, 2024), and well-informed site selection for floating wind will therefore be important in reducing spatial impact on fishing. Furthermore, lessons learned from the development of the Hywind Tampen floating offshore wind farm (Utne-Palm *et al.* 2025) stress the need to include and address the concerns of the fishing industry in siting future developments.

Notwithstanding the need for management to prevent overfishing and enable fish stocks to recover, ensuring equitable access to marine resources will be crucial to support the UK fishing industry. Identification and protection of valuable and important fishing grounds therefore provide a key input to OGP. With less fishing activity and fewer overlaps with other sectors, a sub area of the northern ENS has been defined as the 'North East area of opportunity' for future offshore wind development by TCE (Fig.15b). However, the extent of the spatial footprint of future floating wind projects is likely to have major implications for fishing activities in other areas of the UK's EEZ. To prevent permanent exclusion, minimising future overlap and implementing design that permits safe entry into future offshore wind developments is needed. In both wind farms and MPAs, deployment of low impact fishing techniques and technologies that balance the need for sustainable and environmentally acceptable fishing could allow continued activity and co-location.

Navigation, access and safety

Displacement of other sectors (e.g. fishing and recreational sailing) is likely to result in increased multi-sectoral use within major shipping routes. In parallel, higher levels of marine traffic combined with a greater number of physical obstructions (wind turbines), contributes to the risk of collision and allision (vessel impact with a stationary structure). Examples include the recent incidents between a tanker and a cargo ship (MAIB, 2025) and between vessels and offshore structures (HSE, 2025). Other risks to safety and navigation include areas with route crossings (e.g. between port approach channels and coastal shipping routes), the potential for grounding on shallow sandbanks, and radar interference near offshore wind sites.

Maintaining access to ports and offshore infrastructure means it will be vital to manage and protect key shipping routes including crucial deepwater routes through constrained areas for tankers, cargo, ferry and other large vessels. The Nautical Institute and World Ocean Council (2013) indicate that safety margins required for ship manoeuvring of the largest vessels can extend the claim to space for a single vessel to around 3km (turning or stop distance based on six times a ship's length plus 500m buffer). An obstacle free buffer zone of 2nm (3.7km) is suggested to separate shipping lanes from infrastructure. In the busiest shipping areas, the recommendation that space for up to four vessels to pass at a distance of two times a ship's length plus a buffer zone could result in a spatial claim for lanes of up to 10.5km wide between adjacent wind farms.

As a result of current lease agreements for offshore wind, diversion of shipping routes around infrastructure may be required if offshore wind were given primacy (e.g. ABL, 2021,

also see Fig.19a). In the Netherlands, optimisation to allow more efficient use of offshore space was applied in 2013, where shipping lanes were re-routed to make them safer and with fewer crossings (Rijkswaterstaat, 2013). Elsewhere, moving vessel routes further from the US Mid-Atlantic coast has been proposed to allow for cost effective offshore wind developments (Samoteskul *et al.* 2014). Changes to shipping routes are challenging as safety of navigation and communication should not be jeopardised. Moreover, longer, less efficient routes around wind farms incur costs to the shipping industry and can result in increased emissions.

Where oil and gas field production will continue to meet society's needs until and beyond 2050, and if offshore storage operations increase, safe access for supply vessels and helicopters will need to be prioritised. Helicopters used to support the offshore wind industry will also require access for activities including turbine and offshore substation maintenance. Flying level for offshore helicopter transits is generally between 1500-6000ft, however a higher number of offshore wind turbines can create challenges for navigation. This is a particular concern in poor weather conditions, where a low cloud base or 0° isotherm requires operations below 1500ft which may prevent safe vertical separation from obstacles (500ft for visual and 1000ft for instrument flight rules), (CAP 764, CAA, 2024). Furthermore, a separation distance of six to eight times the rotor diameter of a wind turbine has been recommended to avoid the turbulent, low velocity wake in the vicinity of wind turbines (Bakker & van der Geest, 2019). Applying this to a 14 MW turbine with a 222m rotor diameter suggests a separation distance of c.1.3-1.8km (4370-5827ft) could be required and result in the need to fly around rather than over a wind farm in certain conditions. For aviation, safety of navigation measures mean that offshore wind developments are recommended to be designed in such a way as to allow safe transit corridors for helicopters including search and rescue, in line with Marine Guidance Notice 654 (Maritime and Coastguard Agency, 2021).

Threats to power supply and national security

Disruption to energy supply and communications could be catastrophic for the UK. The growing presence and reliance on offshore energy infrastructure and the many associated connections along the UK coastline means their security is of critical importance. Despite growing awareness of the issues, offshore infrastructure is argued to be insufficiently protected (e.g. Sunak, 2017). Incidents of suspected sabotage of gas pipelines and undersea cables in the Baltic Sea (e.g. Allison, 2024) have exposed the vulnerabilities, threats and risks of deliberate damage to subsea infrastructure.

The Royal Navy is tasked with protecting undersea critical national infrastructure (House of Commons Defence Committee, 2021) and several initiatives are underway to increase defence capability and subsea surveillance in the maritime domain (Ministry of Defence, 2025). In addition, strengthening of legal protection for critical maritime infrastructure and deeper cross border collaboration with Europe to improve security have recently been proposed (Sari, 2025).

Optimising placement of new offshore infrastructure in light of security concerns will be a crucial element of future geospatial planning. In Australia and New Zealand, Cable Protection Zones have been established to minimise damage from fishing and shipping and to closely monitor maritime traffic in high value communication zones (Australian

Communications and Media Authority, 2025; New Zealand Ministry of Transport, 2025). The need for increased defence and maritime security activity can also impact location of future projects. In a recent decision taken by the Swedish government, maintaining the country's ability to detect and respond to a missile attack, resulted in the rejection of applications for 13 offshore wind farms in the Baltic Sea (Reuters, 2024).

Introduction of restricted areas and future strategy for locating subsea developments (e.g. wide geographic spread versus clustered routes and infrastructure) have consequences including loss of access, displacement of activities and implications for offshore safety. Yet, as competition for space intensifies, the need for more subsea infrastructure indicates the importance of integrating offshore planning with security priorities. Given the need to respond to incidents efficiently, it will be crucial to factor in the spatial requirements to allow surveillance, maintenance and where necessary, any repair works.

Siting offshore wind

The UK government's Clean Power 2030 action plan includes the ambition to increase offshore wind capacity from the 14.7 GW available at the end of 2024 to 43-50 GW in 2030 (UK Government, 2024). To meet the high-end estimate of 50 GW requires 2521-3530 (assuming 10-14 MW) turbines to be installed at a rate of between 420-588 per year from the end of 2024. A total of 586 turbines were reported to be under construction at the end of 2023 for wind farms that will come online between 2024 and 2027 (TCE, 2024b). This is the same number reported at the end of 2024 reflecting that no new offshore wind projects were fully commissioned that year (TCE Offshore Wind Report, 2025c). Despite the high ambition of government, the slow delivery of offshore wind reflects challenges in the supply chain, increased costs, and grid constraints. Combined with policy uncertainty and delays in consenting and permitting, the attractiveness of investment in offshore wind has declined.

The UK's Contracts for Difference (CfD) scheme is a mechanism to support low carbon electricity generation and de-risk investment whereby a 'strike price' or fixed price for electricity is submitted by developers. If the market price is below the strike price, the developer gains a top-up from the government, and if it is higher, they pay back the difference (DESNZ, 2025i). Following the absence of bids for offshore wind in CfD Allocation Round (AR) 5 due to a low cap on the strike price, government measures to increase investment in AR6 lead to 5.34 GW of offshore wind capacity being awarded in 2024. In early 2026, a further 8.4 GW was awarded in AR7. The outcome of AR8 and delivery of all projects prior to 2030 will be crucial. With factors including supply chain, skills, infrastructure and grid constraints still to resolve, the 2030 target is severely challenged and may no longer be attainable. Conversely, a slower pace of deployment buys the time to address spatial planning issues relevant to future areas of development.

Challenges facing co-location with offshore wind may look different in future. Advances in technology may enable deeper water fixed foundations whilst the development of larger turbines with higher efficiency will require wider spacing. For example, turbines rated up to and beyond 20 MW are expected to feature in wind farms with a post 2030 final investment decision (IRENA, 2019). While future fixed wind developments have the potential to be less restrictive, the introduction of floating wind introduces a larger spatial requirement for mooring and the potential to severely impact access to other sectors. Furthermore, balancing the need to be compatible with other marine sectors while optimising the layout of

wind farms for operational efficiency, managing wake induced turbulence (e.g. Sickler *et al.* 2022) and impact of 'wind theft' on neighbouring and cross border wind farms (e.g. Pryor *et al.* 2021; Finserås *et al.* 2024) adds further complexity associated with placement of new developments.

Offshore geospatial plan for the ENS

As sectors and stakeholders seek to achieve their respective goals in line with energy, climate, environmental and biodiversity targets, competition for space will further intensify. To help shorter-term planning efforts for human-based activity, insights gained from the review of activities are integrated into a near future (c.2030) geospatial plan for the ENS (Fig.22) and used to develop a simple decision workflow (Fig.23). Recognising that the social and political drivers that shape energy policy and impact marine use are constantly evolving, the aim is not to prescribe a specific outcome for any individual activity but offer a forward-looking view to help guide future decision-making.

1. There is no flexibility in site location for subsurface resources as they are dictated by the geology. Fig.14 represents a starting point to begin to refine and screen out areas of potential conflict between subsurface use and offshore wind and has been used to define a co-location area. If sites suitable for subsurface use are within the co-location area, then initially, subsurface could be given priority unless technical evaluation reveals lack of a viable site. If a viable site is confirmed, a spatial co-location solution could allow both projects to proceed. For example, this could be as simple as adjusting the boundary of a planned wind farm such as that recently undertaken in the Netherlands to enable new gas platforms to be located (see Kombrink, 2025).
2. Oil and gas licences where remaining resources exist, and areas adjacent to a current licence (e.g. current production, undeveloped discoveries and stranded gas), could be reserved until such time as they are depleted and abandoned or deemed unviable for production. Such a strategy could support the objectives for maximising societal and economic value of an activity outlined in the North Sea Future Plan (2025) prior to transitioning areas and the workforce to carbon storage.
3. Key fishing grounds that are currently not within an operational or planned wind farm are indicated and could be reserved or prioritised. Subject to fisheries management restrictions and bylaws, fishing continues to be allowed everywhere.
4. Areas with the busiest shipping routes are shown. Their protection can ensure no development occurs in areas that could affect efficient transit of large vessels and access to ports.
5. The cables and pipelines shown include several planned CCS pipelines (e.g. Viking and Endurance CCS projects). Prioritisation and protection of critical infrastructure could mean seeking synergies with other offshore use to minimise impact on other sectors and allow shared monitoring and security solutions.
6. For many sectors, co-location could become the standard solution where benefits to wider multiple stakeholders are identified. As offshore wind is currently too prejudicial to many existing stakeholders, the ability to deploy co-location solutions will be essential to minimise and mitigate conflict.

With a higher degree of confidence relating to where certain activities can and cannot go, other potential use is more uncertain. For example, aggregate resources which will be

present within the areas shown in Fig.18a cannot yet be identified at a scale useful for detailed offshore planning without use of high-resolution data. The possibility for other offshore use is also included in Fig. 22. Currently, there are no wave and tidal projects in the ENS although considerable potential is recognised elsewhere in the UK, predominantly on the west coast (Coles *et al.* 2021; Jin & Greaves 2021). In the ENS, a small area with potential for future tidal stream projects has been highlighted off the coast of Norfolk (MMO, 2013b). In the aquaculture sector, several areas with potential for future activity have also been identified (MMO, 2013a).

In the marine environment, present and future human activities are likely to have a variable impact on individual species that will differ by location. Future detailed work is therefore needed to fully integrate the presence of 'silent' stakeholders into OGP. Synergies with the marine environment should be explored alongside scenarios investigating cumulative impacts including the consequences or benefits of co-locating offshore activities.

Discussion and implications

The extent of offshore use in the ENS results in a high number of overlapping activities, each with their own spatial constraints and varying levels of compatibility. Challenges are associated with the growing presence of, and need to protect, infrastructure alongside increased awareness of human impact on environment and biodiversity which is driving further measures to restrict use of offshore space.

With a high capacity for geological subsurface storage beneath an area of significant potential for offshore wind, the southern ENS faces a major geospatial challenge as each sector competes for space, yet both technologies are vital for meeting net zero targets. Presence of other users of the subsurface, seabed, water column and airspace exemplify offshore planning as a multidimensional problem, primarily spatial but with a temporal component associated with the dynamic nature of some activity (e.g. fishing and offshore leasing/licensing periods).

The demand for space will undoubtedly increase as further seabed leasing rounds are announced and more wind farms are consented to help meet renewable energy targets. It could further intensify if government policy restrictions on no new oil and gas licences are revoked. As use of the marine area evolves, complex technical and regulatory challenges arise from the need to reduce and manage conflict between sectors, while simultaneously seeking to optimise economic, social and environmental objectives relevant to stakeholders, local communities and government.

Surprisingly, areas of research interest for the UK government's CESM neglect to explicitly consider the role of offshore spatial planning in delivering net zero and clean power (DESNZ, 2025e). Addressing this knowledge gap would ensure that spatial challenges resulting from the offshore deployment of wind and subsurface use are not overlooked. Therefore, the data and evidence in this study is an essential element that could and should contribute to framing the CESM thematic research needed on whole systems, place-based and cross-sector approaches required to underpin a successful energy transition.

Using the ENS as an example and with an emphasis on subsurface use, we have compiled a comprehensive database of offshore activities. The review and interrogation of which demonstrate the need to shift away from single-sector perspectives towards a more holistic,

evidence-informed and interdisciplinary approach. Insights and lessons learned from the ENS have broader implications for addressing offshore spatial planning challenges in all regions of the UK's EEZ and in other countries. Our solutions stress the need for integration of the subsurface into offshore spatial planning decisions and recognise that policy interventions are required to address co-location challenges.

Recognising the role of the subsurface in the energy transition

Our review of offshore activity shows that prioritisation of offshore wind could effectively rule out areas of the seabed for alternative use and result in loss of access to geologically constrained subsurface resources. Incentivisation of offshore wind (e.g. the Clean Industry Bonus, DESNZ, 2025j), its higher level of technological maturity, and the lack of a commercial model for CCS adds urgency to the need to identify potentially viable project areas if the subsurface is to play a role in the UK's decarbonisation.

It is also important to recognise that historically, many published headline values of storage capacity are likely to have been overestimated. In recent years, detailed analysis of the subsurface and site-specific conditions has revealed constraints that can impact capacity (e.g. geological heterogeneity, aquifer pressure). As each site is unique, comprehensive evaluations, which can take years to complete, may ultimately render a site ineffective for storage due to geological and/or non-geological risks (including the presence of legacy wells which can compromise storage integrity). Reserving the best potential subsurface sites for future use is therefore crucial in areas with suitability for offshore wind. Conversely, ruling out sites will be just as important so that areas can be made available for alternative use. Independent verification of storage site potential should be provided by the regulator prior to any decision. However, at such an early stage of CCS in the UK, there are still uncertainties associated with subsurface use for storage, some of which may only be fully addressed once data becomes available from operational projects.

This study demonstrates the importance of considering the potential future role of the subsurface for the energy transition using an example from a mature petroleum province where there is also intent to repurpose facilities and infrastructure. Recognising there may be suitable sites (e.g. for saline aquifer CO₂ storage) in regions where the subsurface had limited or no previous role (e.g. some parts of Ireland), highlights the need to evaluate and factor geological storage potential into future planning decisions in any offshore area.

Trade-offs, choices, consequences and solutions

Managing offshore activity is increasingly complex with numerous trade-offs and consequences possible and where assigning priority to one sector may mean sacrificing the goals of another. Recognising areas important to each sector provides insight into flexibility in terms of what can and cannot be moved and the potential knock-on effects of decisions. Successfully minimising conflict therefore requires oversight of where activities are present and why; where future problems may arise (regret factor); mechanisms to promote co-location and temporal solutions; and recognition that in timely decision-making, achieving long-term goals may require short-term solutions.

The diverse range of stakeholders with claims and interests in the ENS and the UK's wider EEZ means it is simply not practical to segregate all activities. Co-location can aid resolution of spatial problems associated with allocation of marine space and could be essential to

avoid compromising the goals of individual sectors. Within the large footprint of a wind farm this could enable overlap with subsurface activities to optimise the area for both energy transition and net zero targets.

Integration of data from multiple sectors allows cross referencing of preferred locations for marine activities. Raising awareness between sectors, stakeholders and regulators can promote collaboration and development of co-location solutions. Therefore, in line with the vision outlined in Section 2.3.1.5 of the Marine Policy Statement (2011), the results and approach from this study can be used to indicate locations where a range of activities may be accommodated to encourage co-location within the marine area.

Furthermore, this work could be used to independently inform spatial planning scenarios for energy infrastructure and security, providing insights relevant to linking offshore energy and subsurface storage to onshore transmission networks. Detailed knowledge of offshore use therefore has implications for future iterations of strategic energy planning such as that currently being undertaken by NESO (2025b) to identify and map the location of onshore infrastructure required for an integrated energy system.

To effectively address current uncertainties, OGP requires a dynamic management strategy with the ability to adapt to evolving challenges and opportunities. For example, a compromise to achieve more offshore wind in the near-term could involve leasing over potential storage sites that are currently viewed as less favourable but could be developed in future with the benefit of experience gained from other projects. This temporal solution allows time for development and upscaling of CCS technologies during the 25-to-30-year lifespan of a wind farm and the potential future market for CO₂ sequestration to emerge. In this scenario, full decommissioning of the wind farm, rather than replacement (due to availability of larger more efficient turbines in future) is assumed.

Other decisions can have permanent effects. The increased presence of offshore wind has consequences for exploration activities that may be much harder to address should a government reverse the current (April 2026) position on oil and gas activity. This could include revoking the commitment to 'no new licences' to contribute to energy and economic security through domestic production and scrapping the Energy Profits Levy (EPL) earlier than planned, to promote investment and growth.

It may be possible for mutual benefits to be derived through co-location and collaboration between stakeholder groups. For instance, encroachment of fishing grounds suggests a need for active engagement with the fishing industry to identify and conserve areas for continued access. If offshore wind could act as a MPA and it can be demonstrated to lead to recovery and proliferation of fish species, there may be synergies applicable to offshore planning through locating these areas adjacent to fishing grounds which in turn can benefit from any spillover effect.

With no physical boundaries in the wider North Sea area, offshore planning should not be taken in isolation. Cross-border spatial coordination with other countries facing the North Sea could enable increased energy trade with Europe and help to provide energy security and independence for the region. Knowledge and data relating to the UK's offshore use can therefore contribute to several European-based projects and initiatives which aim for collaboration of the North Sea countries at a basin-scale. This includes building on work to

understand the potential for synergistic use of the North Sea and offshore energy integration (e.g. North Sea Energy Program, Satish *et al.* 2025). Other projects include basin-wide planning for energy infrastructure including long-term onshore and offshore grid planning (North Seas Energy Cooperation; NSEC 2024); and the Greater North Sea Basin Initiative (GSNBI), a platform for spatial integration (GSNBI, 2023). However, optimising cross-border offshore use at a regional scale, brings additional challenges in collaboration, data sharing and regulatory alignment with the European Union.

This study is predominantly a technical-led approach to provide the evidence needed for recognising trade-offs between activities in the subsurface, seabed, water column and airspace to enable informed scenario planning and effective decision-making. While GIS based analysis can provide a systematic and logical approach to spatial decision-making, a more formal approach could be applied using multi-criteria decision analysis (MCDA). This method allows evaluation of criteria relating to multiple sectors and requires wider engagement with stakeholders. The process aims to assess and compare alternatives and apply a weighting to score them to determine an order of preference for the available options. Due to the large number of alternatives (marine users), any attempt to undertake MCDA for offshore planning will be complex. With a strong subjective component involved, there is a substantial risk of assumption and bias when weighting and assigning 'performance' values. This can compromise meaningful output or result in an oversimplified model (e.g. Kujawski, 2003). Therefore, as a tool to aid decision-making, MCDA can support the process however, the highest-ranking option may not ultimately be the preferred choice once socio-political factors at the time are considered. As this study demonstrates, management of offshore use and activity is not just about finding the single 'best' solution. It is about providing evidence to support informed choices, promoting a shared understanding of offshore use to drive innovative, mutually advantageous solutions and where possible, to solve for multiple users in the same space.

Successful application of OGP therefore requires an interdisciplinary approach to build an integrated and holistic picture of all sectoral interests, a broad scope which makes it challenging to achieve all its objectives (e.g. Ehler *et al.* 2019). A significant amount of knowledge and data are available from individual sectors. However, as recent examples of conflict between stakeholders in UK waters suggest, information is not always easily distributed or understood across sectors, decision-making bodies or government departments. Appreciation of how, why, when and where marine areas are used can improve offshore planning, provide early sight of other activities, reveal constraints and identify potential areas of conflict. Mapping of these activities aids communication and discussion between stakeholders, regulators and the public. However, it can only be effective if information is made available across all sectors and organisations. This includes practical and technical information relating to the spatial requirements for offshore use and recognition of areas with a potential future use.

Limitations and recommendations for future work

An awareness of the offshore spatial squeeze and its potential to threaten progress of the energy transition is relatively recent. The various sectors and technologies are difficult to navigate, consequently there are very few examples of other relevant studies. Single sector focus and strong environmental and ecosystems perspectives, while valid, fail to capture and address the joined-up thinking required to upscale and integrate energy transition

technologies. This ambitious attempt to collate and review information relating to sectors active in the ENS, demonstrates the challenges faced in a congested marine area. It establishes a practical approach to OGP and emphasises the importance of the data that underpins the ability to address future challenges.

There is a vast amount of data and publicly available information relating to marine activity. Despite this, challenges associated with capturing the relevant information included: 1.) locating data sources; 2.) locating the most up to date information and 3.) translating data into a suitable format. While the most up-to-date version of an available dataset was used in this work (see Supplementary material: Appendix A), different datasets can span different years and are not necessarily an accurate representation of current use. Examples encountered include inconsistent attribute data and the availability and status of telecommunications and interconnector cable data. This highlights a limitation with the current work which could be eliminated in future studies if datasets were regularly updated, made available in a consistent format and stored in a centralised and accessible database.

Use of GIS allows underlying datasets to be rapidly replaced, outputs and scenarios to easily be updated and crucially, the generation of maps to communicate key insights and information to a wide audience. Using the information for strategic decision-making requires contributions from a range of stakeholders, regulators and research. While we recognise the importance of stakeholder input, the focus of the study was predominantly on the technical challenge and practicalities associated with developing and applying effective OGP.

The study emphasises offshore geospatial planning as a major interdisciplinary challenge area. The findings reveal wider knowledge and literature gaps and generate topics of interest providing insight into new areas of research. These include the need to understand viability of geological resources, effective co-location technology and techniques across all sectors, geological limitations of seabed use (e.g. glacial hazards) and the ecological impact of decommissioning wind farms at the end of their useful life.

Proposal for an overarching regulator

To date, spatial planning has *not* been given a prominent role in managing the UK's offshore area. The licensing and leasing of areas is traditionally undertaken on a first-come-first-served basis. Deficiencies in single sector regulation have led to uncoordinated decision making and lack of consistent strategy, highlighting the challenges associated with siloed thinking and promotion of individual sectors and technology. This study includes examples of the resulting conflicts and demonstrates that there are negative consequences and trade-offs that may not be immediately obvious when prioritising one use over another.

The regulatory system has not kept pace with the changing use and need for offshore space. As marine use intensifies, disputes between sectors with overlapping claims or interests are likely to increase unless regulations are introduced and enforced. There is a current lack of guidance and of any arbitration mechanism to decide primacy when spatial conflict occurs between multiple sectors. It is left to stakeholders and their regulators to come to agreement through compromise or compensation measures which can be financial (e.g. between offshore wind and subsurface use or the fishing industry), or physical (e.g. expansion of marine protection areas). Consequently, the present 'solutions' risk failure in adequately

addressing the best use of space, result in lost opportunities, disadvantage sectors with weaker influence, and incur costs associated with a dispute.

With clean energy a key part of the net zero strategy it will be important to find solutions that enable the energy transition alongside social, environmental and sustainability objectives. To provide for society and meet sustainable development goals there will be unavoidable consequences for the environment which need to be minimised by managing use of resources in a responsible and fair way. To achieve this requires oversight and knowledge of the whole offshore area with stakeholder and regulator agreement for co-operation and collaboration. Assessment of trade-offs and input to binding decisions should be transparent and in the public interest.

Despite far fewer spatial conflicts, the fragmented nature of governance of the maritime area has been recognised in Ireland. The need for *'orderly, timely, proper and sustainable management of the marine area while also protecting the public interest'* led to establishment of the Maritime Area Regulatory Authority (MARA) in 2023 (MARA, 2025). MARA is an independent state agency set up to significantly reform marine management through a new streamlined consenting and licensing system. The need to adapt to the changing use of offshore areas was also recognised in the United States of America which led to the creation of the Bureau of Ocean Energy Management (BOEM) in 2011. BOEM *'promotes energy independence, environmental protection, and economic development through responsible, science-based management of energy and mineral resources on the U.S. Outer Continental Shelf'* (BOEM.gov, 2025).

This study has highlighted and exposed the challenges associated with offshore use in the ENS and illustrates the urgent need for improved organisation and management of offshore areas. Possible solutions include improved coordination between existing bodies or an alignment of bodies with advanced roles and responsibilities. However, with similar issues emerging elsewhere in the UK's EEZ, there is an opportunity to respond in a practical yet equitable way to ensure optimal use of offshore space, maximise the chances of the UK meeting its emissions targets and realise its ambition of a clean, secure energy supply.

To achieve this, we propose that a single overarching regulatory body is established that has decision-making power and processes that enable clear sight of all options for offshore use. All current regulatory and licensing/leasing bodies could still exist and feed into an overarching framework. Such an organisation or Lead Regulator needs to be populated by informed yet independent experts who have no vested interest in the outcome. Furthermore, a unified licensing regime for energy to include oil and gas, offshore wind, subsurface storage (of natural gas, CO₂ and hydrogen) would enable effective and efficient planning and management for the energy transition.

Policy will need to be responsive and proactive to evolving offshore dynamics and challenges to drive spatial and temporal solutions. Adopting this approach would also improve integration across the energy sector, strengthen links with onshore systems and national security, promote cross border collaboration and ensure that data management processes underpin a reliable evidence base for future OGP.

Conclusions

Achieving the UK's emission targets and acceleration of the energy transition will increase spatial pressure in already crowded offshore areas. A comprehensive review of the broad nature of offshore use in the English North Sea provides evidence of the spatial challenge and underlines the urgent need for integrated offshore geospatial planning to address the merits, competition and conflict that result from overlap between different sectors. With a strong focus on the critical role that the subsurface plays in delivering the energy transition, we stress the importance, distribution and future potential of crucial geological resources. Overlapping activities and single-sector regulation can cause access to potential subsurface resources to be lost, threatens loss of key fishing grounds, has consequences for the human impact on ecosystems and biodiversity, presents challenges to navigation and safety at sea and has implications for national security and siting of future offshore wind projects.

The results of our research raise awareness of issues that, if left unresolved, threaten net zero and energy transition targets within the currently prescribed and legally binding timeframe. Moreover, there is lack of a legal framework to promote coordination between sectors, their individual regulators and government departments. Crucially, the need for arbitration where conflict arises results in our proposal for a single overarching regulatory body and unified licensing regime. If the political ambition of the current UK government to become a Clean Energy Superpower is to be realised, it will be essential to optimise resource management and geospatial planning in a fair, equitable and effective way for all offshore users.

Recognising that both socio-political context and marine use changes with time there is also a need to ensure continued availability of spatial data to allow offshore planning to evolve with changes such as the status of licence awards. To our understanding, this study is the first independent attempt to consolidate existing knowledge, identify the key issues, address the trade-offs, and seek workable solutions using offshore geospatial planning to deliver the energy transition. The data and evidence from the ENS form a basis upon which to design a whole systems approach to enable informed decision-making and promote co-location solutions. The results have a potential to shape future marine policy in the UK's Exclusive Economic Zone and in other nations facing complex geospatial challenges.

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Author Contributions

RVH: Conceptualisation (equal), Methodology (lead), Validation (lead), Formal analysis (lead), Investigation (lead), Data Curation (lead), Writing – original draft (lead), Writing – review & editing (equal), Visualisation (lead), Project administration (lead). **JRU:** Conceptualisation (equal), Writing – review & editing (equal), Funding acquisition (lead).

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Declaration of competing interests

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

This study was maintained as a working document until the end of January 2026. Any errors or omissions are the responsibility of the authors.

The publication is supported by multiple datasets, which are openly available at the database locations cited in the reference section. Due to the large volume of data sources used, a full list and links to data source layers can be found in Supplementary material: Appendix A.

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Figure Captions

Fig.1. UK energy consumption and electricity supply by source since 1990. (a) Primary fuel consumption in the UK. Primary fuels refer to resources before they have been transformed into useable energy. (b) Electricity supplied and evolution of the energy mix (total electricity supplied plus imports). Electricity generation from coal, oil and gas has dropped from 76% to 29% over this period. In 2022, the UK became a net exporter due to increased demand from France. Data sources: DECC, 2014a; DESNZ, 2025a, 2025b).

Fig.2. Overview of past electricity generation and GHG emissions (DESNZ, 2025a, & 2026a) alongside future possible scenarios. Electricity and emissions projections (EEP) provide a baseline scenario to show the expected outcome if no '*policies at an earlier stage of development were implemented*' (DESNZ, 2026b). Future Energy Scenarios (FES) are from National Energy Systems Operator (NESO, 2025a). Carbon Budgets (CB) 1-5 and Nationally Determined Contribution (NDC) for 2030 and 2035 relate to Territorial GHG emissions only, CB 6 and 7 include additional emissions from International Aviation and Shipping (IAS), (DESNZ, 2022 & 2025d).

Fig.3. GHG emissions from 1990 and 2023 by Territorial Emissions Statistics (TES) sector, clockwise largest to smallest. Proportion of CO₂ emissions are shown in outer circle (data is final for 2023, source: DESNZ, 2025c).

Fig.4. Comparison of point source emissions (carbon converted to CO₂ emissions) from (a) earliest available data (2005) to (b) most recent (2023). (a) The 50m depth contour indicates favourable areas for fixed offshore wind, (b) Presence of carbon storage licences and offshore wind leases in the Southern North Sea introduce competition for space. Data sources: © Crown 2026 copyright Defra & DESNZ via naei.energysecurity.gov.uk, licenced under the Open Government Licence (OGL); information provided by the North Sea Transition Authority and/or other third parties (2025b); data provided by The Crown Estate that is protected by copyright and database rights (2025d); public sector information, licensed under the OGL v3.0, from Crown Estate Scotland (2025); data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl.

Fig.5. Terminology for areas referred to in this review. (a) The extent of the UK EEZ with the English North Sea area highlighted. (b) Marine plan areas in within the English North Sea, based on bathymetry (after MMO, 2014). (c) The Southern and Central North Sea areas as defined by the British Geological Survey (Cameron *et al.* 1992; Gatliff *et al.* 1994).

Fig.6. Distribution of claims and interests relating to current human activities identified within each domain. (a) Subsurface. (b) Seabed. (c) Water column. (d) Airspace. Activities are shown in ENS area only. Labels, layer definitions and descriptions are provided in Tables 1.a-d. Individual data sources included in Appendix A. Data sources: Contains information provided by the North Sea Transition Authority and/or other third parties (2025b); data provided by The Crown Estate that is protected by copyright and database rights (2025); public sector information licensed under the Open Government Licence v3.0, from Crown Estate Scotland (2025); data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; UK Hydrographic Office © copyright and database right 2020; UK EEZ Ships' Routing Measures as approved by the International Maritime Organisation (IMO), and/or the Maritime and Coastguard Agency (MCA) (as National Competent Authority), (IMO, 2025). Joint Nature Conservation Committee data © copyright and database right 2020; Natural England data © copyright and database right 2020; © Marine Management Organisation copyright and/or

database right 2023. All rights reserved; Data courtesy of National Air Traffic Services (NATS) (2025).

Fig.7. Heat map showing number of overlapping claims and interests resulting from human use in the English North Sea as defined in Table 1 and Fig.6a-d. Up to 12 overlaps are identified in some areas. Map contains current and planned activities based on available data within the UK EEZ, correct as of January 2026. Sources available in Appendix A.

Fig.8. Total claim for space from stakeholders in the ENS area as defined in Table 1 (a-d). Infrastructure includes all cables, pipelines and structures. Other includes mining, areas of foul ground and areas around protected wrecks.

Fig.9. Compatibility matrix summarising interactions between human activities in offshore areas. Activities where co-location solutions may be possible are identified and an indicative order of priority is shown by the direction of the arrows (expanded after Jongbloed *et al.* 2014). Potential interactions between future offshore wind and other offshore use are shown separately, highlighting the opportunity to optimise offshore space for the energy transition if co-location solutions can be achieved. Infrastructure including cables, pipelines, platforms and wells not yet fully decommissioned are compatible within the area of the licence or lease but are considered hard constraints at a detailed planning scale.

Fig.10. Indicative overview of marine activities/stakeholders and associated organisations with roles in determining offshore activities in England. In addition to these roles, these organisations along with many others can consult and advise on activity across other sectors (e.g. on safety, health, navigation, security). Examples include the Health and Safety Executive (HSE), The Ministry of Defence (MoD), The Fish Health Inspectorate (FHI) and Statutory Harbour Authorities (SHA). Local Planning Authorities (LPA) are included due to the requirement for onshore infrastructure at the land-sea interface. Intended for informational purposes only and to demonstrate the complex nature of offshore management. Data based on information compiled from online sources e.g. organisation websites (accessed in 2025). See Appendix B for acronyms and definitions.

Fig.11. Examples of the technical challenges associated with presence of multiple sectors within the area of the Hornsea-4 wind lease. Includes the area of lease that was pared back to avoid overlap with the Endurance CCS site. CMS = Caister Murdoch System gas pipeline to Theddlethorpe (no longer in use); SEAL = Shearwater Elgin Area Line gas pipeline to Bacton (active). Data sources: Contains information provided by the North Sea Transition Authority and/or other third parties (2025b); data provided by The Crown Estate that is protected by copyright and database rights (2025); data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; KIS-ORCA, 2025c.

Fig.12. Geological maps for key intervals relevant to defining subsurface storage resource areas. Surrounding structural highs that control the location (and limit) of potential storage resources are labelled. (a) Permian (Rotliegend Group) depositional environments showing location of gas fields and undeveloped discoveries with a Leman Sandstone Formation (LSF) reservoir. Location of Carboniferous (Carb.) gas fields and discoveries also shown. CG = Central Graben; BPU = Base Permian Unconformity. (Compiled using data from Gast *et al.* 2010; Steele, 1981; NDR, 2025; UKOGL, 2025; and Brackenridge *et al.* 2020). (b) Permian Zechstein Group depositional environments (based on Z2 cycle) with location of salt structures and areas of undeformed salt. Location of storage caverns within the Z2 (southern cluster) and Z3 (northern cluster) cycles are indicated. Gas fields and discoveries: HE = Hewett; WI = Wissey; VP = Vale of Pickering fields. Gas discoveries: CR = Crosgan; OS = Ossian; PE = Pensacola; WN = West Newton. (Compiled

using data from Browning-Stamp *et al.* 2023; Evans & Holloway, 2009; Garland *et al.* 2023; NSTA, 2025b; Pharaoh *et al.* 2010). (c) Present day distribution and thickness of the Bunter Sandstone Formation showing location of saline aquifer closures with potential for CO₂ storage. An 800m depth contour indicates shallow areas (onshore) and around the crests of some structures. Gas fields: CA = Caister; ES = Esmond; FO = Forbes; GO = Gordon; HU = Hunter; HE = Hewett; OR = Orwell. Saline aquifer: EN = Endurance. (Compiled using data from Bachmann *et al.* 2010; Cameron *et al.* 1992; NSTA, 2025b; Parr *et al.* 2023; NDR, 2025; UKOGL, 2025.)

Fig.13. Seabed characteristics. (a) Bedrock of varying age beneath quaternary sediment cover. Contains British Geological Survey materials © UKRI (2024a & b). (b) Seabed sediment varies in grain size and thickness and results from depositional processes associated with old river systems and previous glacial periods (last glacial maximum shown on Fig.12.c). Areas containing sand and gravel are targeted by the marine aggregates industry, location of site agreements are shown. Contains British Geological Survey materials © UKRI (2024c); and data provided by The Crown Estate that is protected by copyright and database rights (2025). (c) Bathymetry data demonstrates the shallow depth of the southern ENS and important topographical features of the seabed including several tunnel valleys and presence of sand banks. (Contains data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; public sector information, licensed under the Open Government Licence v3.0, from the UK Hydrographic Office (2024); Eaton *et al.* 2020).

Fig.14. Subsurface resources. (a) Composite map of resource areas from Fig.12a-c and current subsurface licenses (Fig.6a). (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict and the need for co-location solutions (from Fig. 9). Overlay contains wind farm areas (TCE, 2025d) and Maritime limits and boundaries from UKHO, 2024).

Fig.15. Offshore wind. (a) Key resource areas with suitability for different types of foundation (as determined by Everose, 2020). (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict and the need for co-location solutions (from Fig. 9). Overlay contains wind farm areas (TCE, 2025d) and Maritime limits and boundaries from UKHO, 2024).

Fig.16. Marine environment. (a) Composite map of areas important to the environment and ecosystem of the ENS. SR = Saturn Reef, NB = Norfolk Banks. (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict and the need for co-location solutions (from Fig. 9). Overlay contains wind farm areas (TCE, 2025d); Maritime limits and boundaries from UKHO, 2024) and 20m contour derived from bathymetry data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; Bird foraging areas and sensitivity to wind farms from WWT, (2013).

Fig.17. Fishing. (a) Composite map of areas important to fishing in the ENS, based on 2019-2022 spatial data available for all gear types (ICES data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl). (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict and the need for co-location solutions (from Fig. 9). Areas with current fishing restrictions shown (see: Seafish Kingfisher Information Service, 2025). Overlay contains wind farm areas (TCE, 2025d) and Maritime limits and boundaries from UKHO, 2024).

Fig.18. Aggregates. (a) Seabed sediments clipped to areas with potential to contain aggregate resources based on sediment class (Folk, 1954); resource categorisation (Bide *et al.* 2011) and a

50m depth cut-off. Contains: British Geological Survey materials © UKRI [2025b]; (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict and the need for co-location solutions (from Fig. 9). Overlay contains wind farm areas (TCE, 2025d); Maritime limits and boundaries (UKHO, 2024); Future aggregates resource areas (Bide *et al.* 2011).

Fig.19. Shipping. (a) Main routes used by shipping in the ENS filtered by frequency of use for all vessels and for all larger vessels (data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl. (b) Heatmap of spatial pressure indicating presence of other sectors with interactions that could result in conflict (from Fig. 9). Overlay contains wind farm areas (TCE, 2025d); Maritime limits and boundaries from UKHO, 2024); 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), (IMO, 2025).

Fig.20. Distribution of legacy items and areas of the seabed related to historical use of the North Sea. Other use includes open waste disposal areas related to offshore wind developments. Data sources: UKHO (2024); EMODnet (2025); OSPAR (2024); Mining Remediation Authority (2025); CEFAS (2024); Roskill, 1954; Hydrographic Department of the Admiralty, 1917. Overlay contains wind farm areas (TCE, 2025d) and Maritime limits and boundaries from UKHO, 2024).

Fig. 21. Overlaps between offshore wind with potential carbon storage sites and undeveloped hydrocarbon discoveries. Licenced and leased areas correct as of February 2025 (TCE, 2025d; NSTA 2025b). For potential loss of subsurface resources in a scenario where no co-location solutions are possible, refer to Tables 3 and 4. Data sources: Contains information provided by the North Sea Transition Authority and/or other third parties (2025b); data provided by The Crown Estate that is protected by copyright and database rights (2025d); data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; and Parr *et al.* 2023.

Fig.22. Indicative offshore geospatial plan for the ENS c.2030. Map is forward-looking and includes key areas of importance for current and future human activity. Areas where emerging technology and innovation could contribute to multi-sectoral use through co-location solutions are indicated. Together with the detail provided in Figs.14-19, the series of maps produced in this study can be used to inform future planning decisions. Data sources: Contains information provided by the North Sea Transition Authority and/or other third parties (2025b) data provided by The Crown Estate that is protected by copyright and database rights (2025d); public sector information licensed under the Open Government Licence v3.0, from Crown Estate Scotland (2025); data downloaded from the EMODnet Portal (2025) (<https://emodnet.ec.europa.eu/en/>), the data originator is Cogea Srl; UK Hydrographic Office © copyright and database right 2020; Joint Nature Conservation Committee data © copyright and database right 2020; Natural England data © copyright and database right 2020; © Marine Management Organisation copyright and/or database right 2023. All rights reserved.

Fig.23. Summary workflow for optimisation of offshore areas with reference to relevant sections of this study.

Table Captions

Table 1. Human use of offshore areas identified in the ENS for (a) Subsurface. (b) Seabed. (c) Water column. (d) Airspace. Distribution of human activities in the ENS are shown in Fig. 6a-d. Layer area definition indicates extent of claim or interest supported by the given description/justification to provide an unbiased and fair representation of offshore use and aid identification of where specific activities are concentrated. For layer source data see Appendix A.

Table 2. Non-human (silent) stakeholder distribution and use identified in the ENS.

Table 3. Gas discoveries in the SNS. Locations are shown on Fig.21. Note that Hawking and Olympus discoveries are located within planned offshore wind sites.

Table 4. Potential loss of subsurface storage resources resulting from offshore wind development. Locations shown on Fig.21. Sites in in bold text indicate overlap of entire resource. Where overlaps are identified with dip slope area (see Fig.17a) extent of storage capacity is not known. Only Bunter closures within CO2stored database have capacity attributed. Not all sites will be viable for storage.

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(a) Subsurface

Activity	Layer definition	Description/justification
Oil & Gas Exploration, Development & Production	Designated licence area	Area containing a resource or with potential to contain/provide a resource (for oil & gas, undeveloped discoveries and stranded gas where production has ceased and reserves remain are included where known).
Gas Storage		All blocks currently under licence issued by North Sea Transition Authority (NSTA).
Carbon Capture & Storage		<i>Note: There are currently no offshore hydrogen storage licences.</i>
Hydrogen Storage		
Mining site	Designated lease area	Area containing a resource or with potential to contain a resource. Currently leased areas issued by The Crown Estate (TCE).

(b) Seabed

Activity	Layer definition	Description/justification
Offshore Wind – Existing*	Designated lease area	Operational sites and sites currently under construction.
Offshore Wind – Planned*		Consented sites and those in planning stages. All current offshore wind leases issued to developers by TCE.
Carbon Storage Lease	Designated lease area	Crown lease issued by TCE. Legal agreement to allow developers to use the seabed for carbon storage activities. <i>Note: To avoid duplication of the same use at this site, only the area of pipeline corridor is used in overlap analysis.</i>
Marine Aggregates	Designated licence area	Area containing a resource (Production Agreement Area) or potential to contain a resource (Exploration and Option Area). All licenses relating to the extraction of marine sand and gravel resources are issued by TCE.
Cables - Power (Inter connectors)	Cable locations with 500m buffer	Interconnectors labelled on Fig. 6.b: B=Britned (UK-NL); NC=NeuConnect (UK-DE); NSL=North Sea Link (UK-NO); VL=Viking Link (UK-DK). UK electrical connections: EGL1=Eastern Green Link 1; EGL2=Eastern Green Link 2.
Cables - Telecom		Buffer applied to indicate spatial requirement for vessels operating within the vicinity of subsea cables (ESCA, 2022). Buffer zones are applied to all cables where data is available in vector format. Consented and planned offshore wind indicates planned cable corridor area. Telecoms cables include both active and not in use. Complete spatial dataset for cables not available. Cable locations
Cables - Wind farm export		

		are approximate.
Cables - Wind farm intra-array		Guidance varies for 'working zones', the spatial requirement for access required for any maintenance, repairs (e.g. boat/anchor clearance) and decommissioning work. A 500m 'working zone' was issued by ICPC (2013). Elsewhere, the German spatial offshore grid plan also recommends a 500m zone each side of a cable (BSH, 2017). However, proximity limits can vary due to conditions, vessels and equipment e.g. Red Penguin Associates Ltd for TCE (2012). ESCA (2017) recommends a 750m working zone.
Infrastructure – Wind turbines & sub-stations*	Turbine locations with 50m buffer	Exclusion zones can be applied 50m from the turbine tower during operational phase which can be in the form of a safety zone (e.g. for navigational safety) or an advisory zone (e.g. for protection of fishermen and structures). A safety zone of 500m is enforced during construction or decommissioning and is applied on a rolling basis to maintenance activities, (Electricity (Offshore Generating Stations) (Safety Zones) (Application Procedures and Control of Access) Regulations, 2007).
Infrastructure – Pipelines	Pipeline locations with 500m buffer	Pipelines labelled on Fig. 6.b: C= Central Area Transmission System (CATS) (UK-UK); L=Langeled (NOR-UK); LO= Lincolnshire Offshore Gas Gathering System (LOGGS) (UK-UK); NP= Norpipe (NOR-UK); S= Shearwater Elgin Area Line (SEAL) (UK-UK). Buffer as per cables description above. A buffer of 500m is based on a review of the German spatial offshore grid plan (BSH, 2013).
Infrastructure – Platforms*	Platforms with 500m buffer	A safety zone of 500m is established automatically around oil and gas infrastructure including platforms, drilling rigs and storage tankers (The Offshore Installations (Safety Zones) Order 2019).
Infrastructure – Wells	Top hole location with 500m buffer	There are no official restrictions or exclusion zones around legacy wells. Buffer has been applied to provide indication of spatial requirement for rig (500m radius) although use of tugboats and anchors could extend the spatial footprint beyond this zone. Space is required for decommissioning and any remediation work to prevent or address leakage from underlying storage sites.
Protected Wrecks	As designated	Wrecks are protected by the Protection of Wrecks Act (1973). Wrecks that are dangerous due to pollution hazard or presence of explosives have specifically designated exclusion zones (Section 2 of the act). Other wrecks designated as historically, archaeologically or artistically important are areas of controlled activity, e.g. no anchoring (Section 1 of the act). The protection of Military Remains Act (1986) protects military maritime graves (aircraft and shipwrecks), and areas may be designated as controlled sites (Designation of Vessels and Controlled Sites, Order 2019).
Foul Ground	As designated	Area with known areas of potential hazard present on the seabed (e.g. anti-mining experiment areas, former coastal bombing range areas), included in dataset available from UK Hydrographic Office (UKHO, 2024).

(c) Water Column

Activity	Layer	Description/justification
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definition		
Conservation – MPA†	As designated	Areas designated by DEFRA to protect species, habitats, ecological processes and geological/geomorphological features of importance.
Conservation – HPMA†	As designated	Highly restricted areas designated by DEFRA for protection and recovery of marine ecosystems.
Aquaculture	Not available	Point data shows location of currently operational sites.
Fishing (Commercial)*	Areas with activity for at least one gear type	Spatial data layers for fishing intensity/pressure are provided for six different gears at resolution of c-squares (0.05° × 0.05°, about 15km ² at 60°N latitude), (ICES, 2021; 2022). Filtering of data is used to indicate areas with differing levels of each type of fishing activity (see Appendix C). Layer definition selected to avoid outcome biased towards an individual gear and is used to identify key fishing grounds relevant to all types of fishing activity.
Shipping	Area with >=1 route per day	Data from EMODnet (2025) is route density at 1km resolution and indicates no square km of the ENS in which shipping was not present for at least one vessel transit in 2024. Layer definition identifies preferential thoroughfares for all marine traffic (includes cargo, tanker, passenger, fishing and other vessels).
Shipping – IMO Ships Routeing	As designated	Pre-determined navigation routes to avoid hazards (grounding) and collisions in congested shipping areas (IMO, 2024). Merged with shipping layer.
Wave & Tidal	Designated lease area	Area of wave or tidal energy development or potential development. There are no leases for wave or tidal energy projects currently present in the ENS.
Recreation	As designated	Spatial data layers indicating non-licensable marine activities (e.g. sailing, boating, scuba diving, from 2019) in and around marine protected areas and sea angling areas in 2020 (MMO, 2023).

(d) Airspace

Activity	Layer definition	Description/justification
Military – Practice & Exercise Areas	As designated	Area used for military training (e.g. low-level flying), weapons trials, surveillance and monitoring of potential threats. Indicated by areas applicable to unmanned aircraft systems in Aeronautical Information Service, National Air Traffic Services (NATS). Areas may not always be active and/or safe altitude boundaries may apply for navigation.
Primary Surveillance Radar	As designated	Areas where structures up to 200m above sea level are in line of sight of a primary surveillance radar (PSR). Identifies where interference with PSR infrastructure is likely and more detailed assessment would be required (NATS, 2025 & CAA(CAP) 764, 2024).
Helicopter Operations - Take off & landing	Location of helicopter decks with 9 nautical mile (16.67km)	Indicates consultation zone prior to placing obstacles that could impact safe flight procedures (e.g. low visibility, missed approach) (CAP 764, CAA, 2024).

buffer		
Helicopter Operations - Helicopter Main Routing Indicators (HMRIs)	Location of centre route line with 2 nautical miles (3.7km) buffer	Indicators of typical and routine routes flown by helicopters to and from offshore destinations (UK Aeronautical Information Publication). Buffer is advised consultation zone for planned obstacles that could impact safe flight (CAP 764, CAA, 2024).
Helicopter Search & Rescue	Not included	No specific routes due to unpredictable nature of search and rescue (SAR) activity. Important to consider need for access when planning or designating offshore use.

* Activities that can overlap domains, e.g. fishing activity is included in the water column but some of this activity can take place at the seabed (bottom trawling); MPAs which can be designated to protect seabed features or for species protection; and offshore wind / platform structures fixed to the seabed.
 † MPAs and HPMAs are designated and defined by humans to protect areas from human impact and therefore considered under 'human use' for this study.

Table 1

Activity	Description
Fish Spawning & nursery grounds	Distribution of spawning and nursery grounds for selected fish species (CEFAS – Ellis <i>et al.</i> 2012). Data indicates the whole ENS marine area is populated by at least one species with highest species diversity close to the coastline and in shallow areas of the SNS.
Seabirds - Breeding & foraging areas	Use of sea areas by seabirds at 3km resolution (WWT Consulting, SeaMaST project, 2013). Data indicates the whole ENS area is used as foraging grounds by at least two species, with highest species diversity closest to the coast.
Seabirds - Sensitivity to wind farms	Combined sensitivity of breeding seabird densities to collision and displacement by windfarms. (WWT Consulting, 2013). Indication of area where bird population would be most sensitive to wind farms (e.g. Bradbury <i>et al.</i> 2014).
Marine Mammals	<p>No digital spatial data available. Maps for 12 cetacean species indicates the importance of the ENS area to at least one species of mammal (Waggitt <i>et al.</i> 2019).</p> <p>Atlas of Cetaceans in NW waters (Reid <i>et al.</i> 2012). Indicates sightings of Minke whale and white-beaked dolphins (in the deeper northern ENS area only) and Harbour porpoises (in all areas of the ENS).</p>

Table 2

Discovery Name	NSTA Cluster Area	Estimated Most Likely Recoverable Resource (bcf)	Reservoir Interval	Data Source
Andromeda North	1	41	Carboniferous	NSTA 33rd Petroleum Round Data packs 1-4 (2022)
Browney	1	2	Carboniferous	
Pegasus East	1	19	Carboniferous	
Pegasus North	1	70	Carboniferous	
Pegasus West	1	83	Carboniferous	
Cobra	2	20	Rotliegend	
Hawking	2	50	Rotliegend	
Olympus	2	23	Rotliegend	
Pharos	2	102	Rotliegend	
Platypus	2	103	Rotliegend	
Copernicus	3	97	Carboniferous	
Kepler	3	109	Carboniferous	
Winchelsea	3	226	Carboniferous	
Cotton	4	24	Carboniferous	
Harmonia	4	31	Carboniferous	
Crosgan	-	Not known	Zechstein	No Info
Ossian	-	Not known	Zechstein	No info
Pensacola	-	320	Zechstein	Deltic Energy (2023)
Selene	-	131	Rotliegend	Deltic Energy (2024)
Total		1,451		

Table 3

Wind Leases		CCS Resources		Legacy wells
Wind Site	Fig.21 Map ref.	Overlap or partial overlap with potential resource and theoretical P50 capacity* of total resource where known		Legacy wells within area of wind site
<i>Name</i>	<i>Code</i>	<i>Name</i>	<i>MtCO₂</i>	<i>No.</i>
Dudgeon	D	Elgood	-	4
		Blythe	-	
Hornsea One	H1	BC26	139	4
		Bunter - other	-	
Hornsea Two	H2	BC1	479	4
		BC26	(as above)	
Humber Gateway	HG	Dip slope	-	0
Inner Dowsing	ID	Dip slope	-	0
Lincs	L	Dip slope	-	0
Lynn	Ly	Dip slope	-	0
Race Bank	RB	Dip slope	-	0
Westernmost Rough	WR	Dip slope	-	0
Dogger Bank A	DBA	Bunter - other	-	2
Hornsea Four	H4	Johnston	19.7	29
		Babbage	33.8	
		Bunter - other	-	
Norfolk Vanguard East	NVE	Davy	15.6	16
		Davy E	3.1	
		Wissey	-	
Norfolk Vanguard West	NVW	Horne	-	8
		Yare	5.3	
		Bunter - others	-	
Hornsea Three	H3	Topaz	0.5	14
		Chiswick	19.5	
		Windermere	-	
		Grove	10.4	
		Bunter - others	-	
Norfolk Boreas	NB	Davy	(as above)	36
		Orwell	37.9	
		Brown	1.1	
		Boyle	-	
		North Davy	3.1	
		South Sean	4.5	
		Wissey	-	
		Bunter - others	-	
Dudgeon Extension	DE	Waveney	7.7	2
		Blythe	-	
Dogger Bank Southeast	DBSE	Gordon	16.5	9
		Cavendish	7.5	
Dogger Bank Southwest	DBSW	Esmond	34.4	15
		Forbes	5.6	

Outer Dowsing	OD	Pickerill	35.7	52
		Malory	13.3	
		Excalibur	21.3	
		Mordred	1.7	
		Galahad	13.2	
		Barque	82.8	
		Barque South	0.1	
		BC22	41	
		BC24	50	
		BC25	31	
Totals			1,134.3	195.0

Table 4

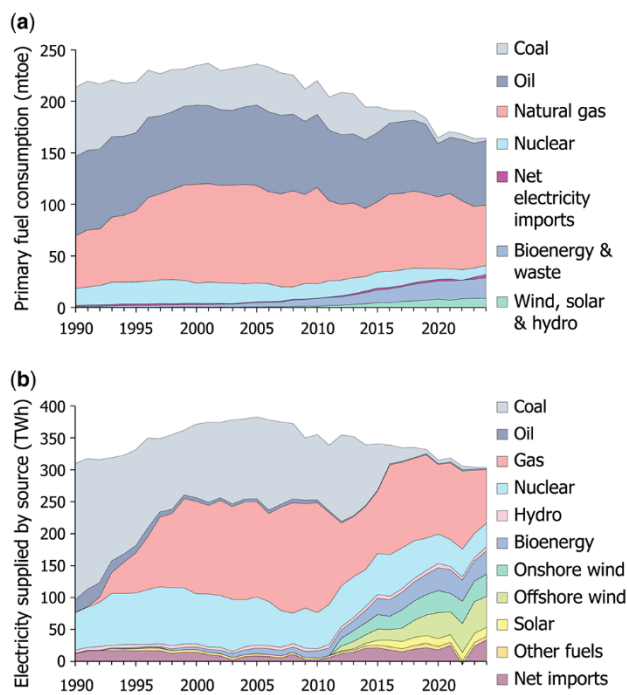


Figure 1

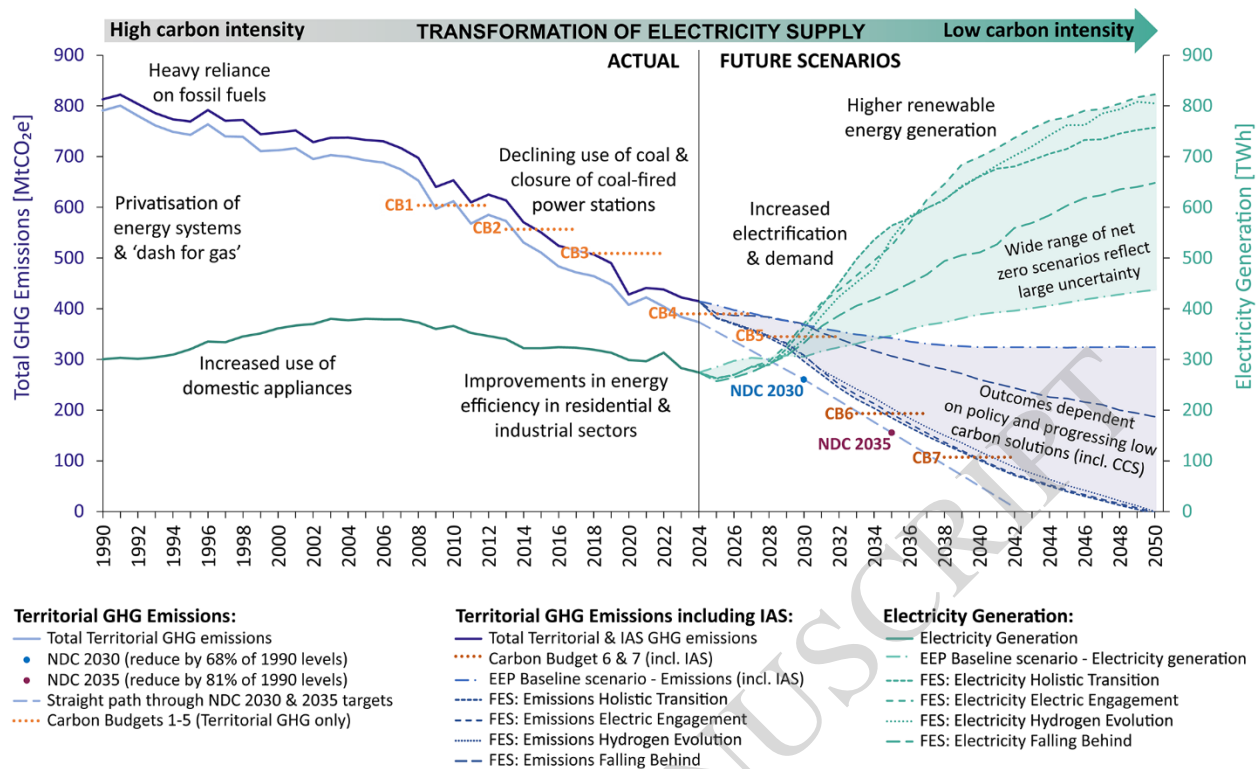


Figure 2

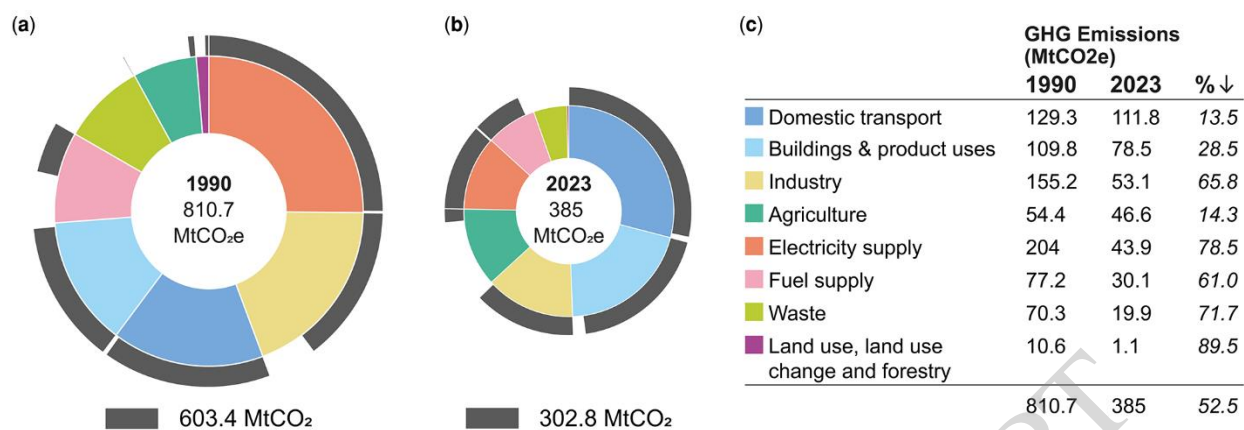


Figure 3

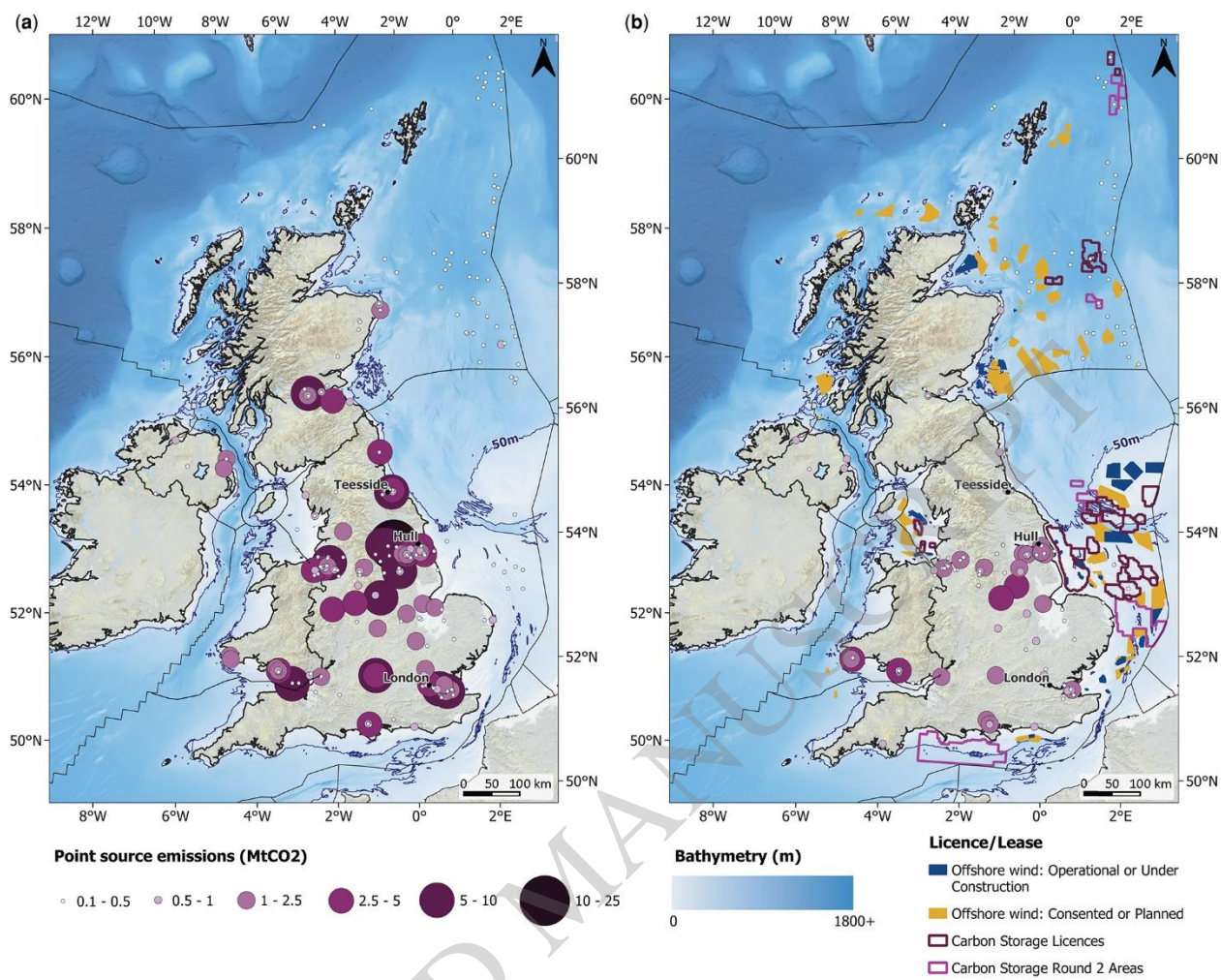


Figure 4

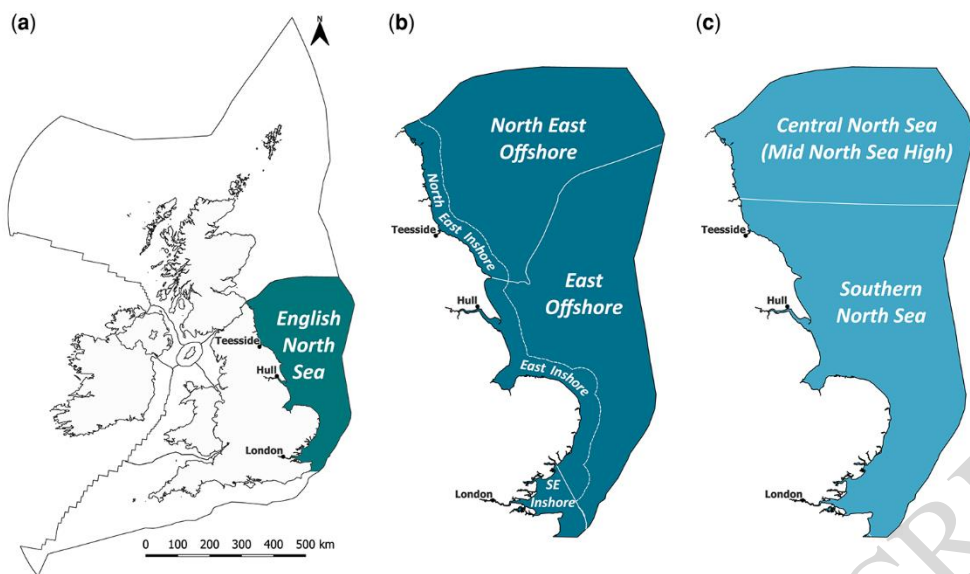


Figure 5

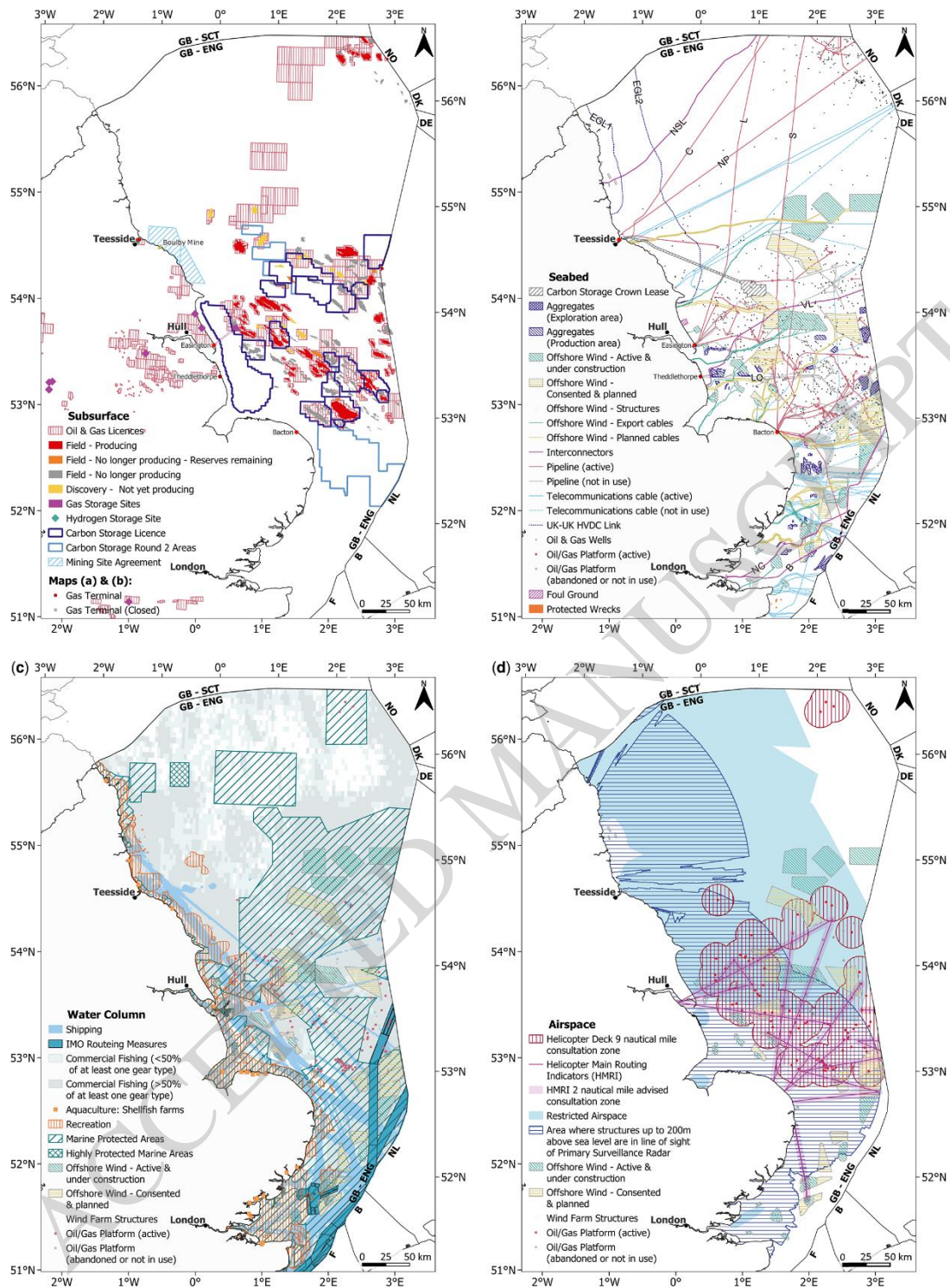


Figure 6

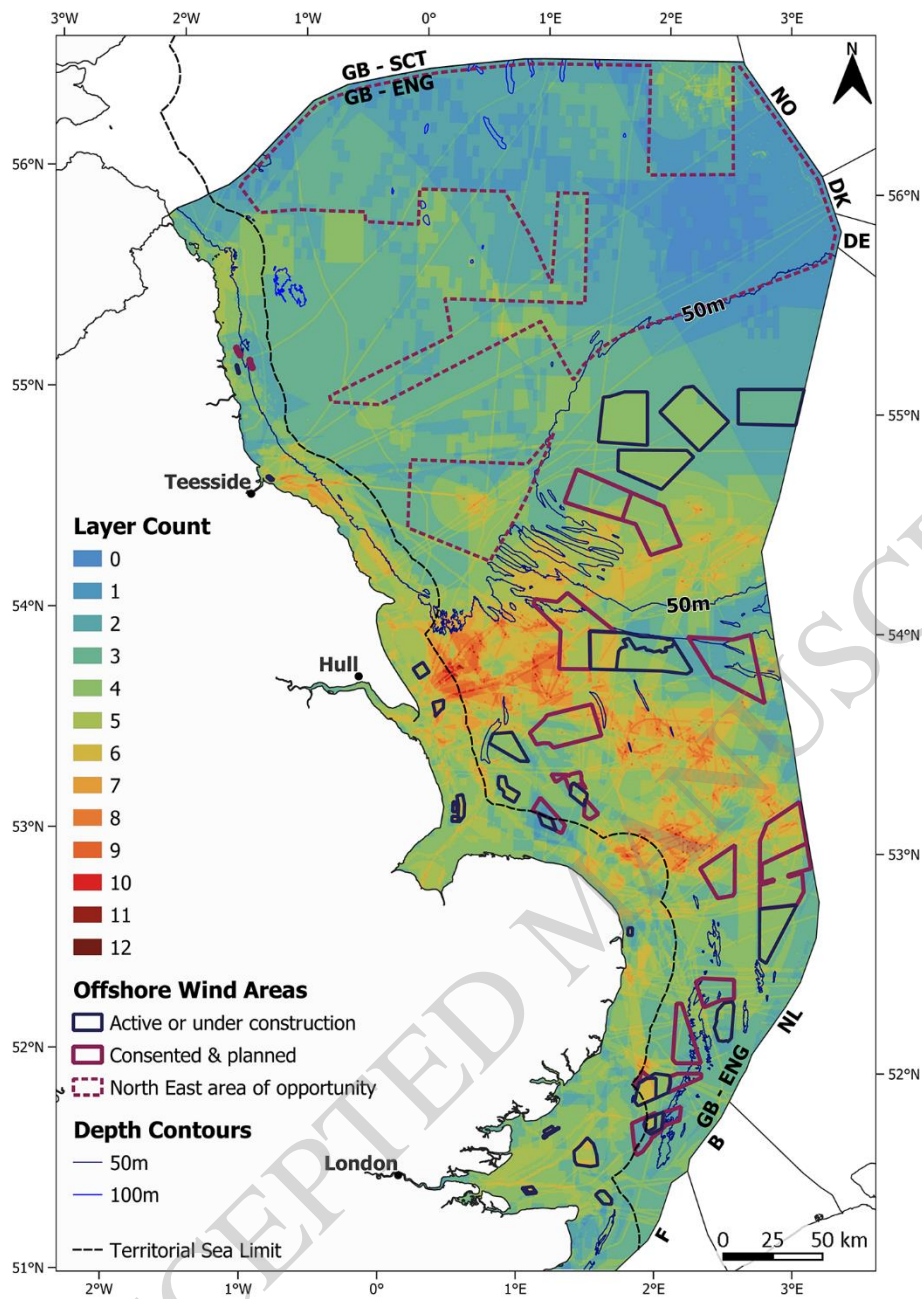


Figure 7

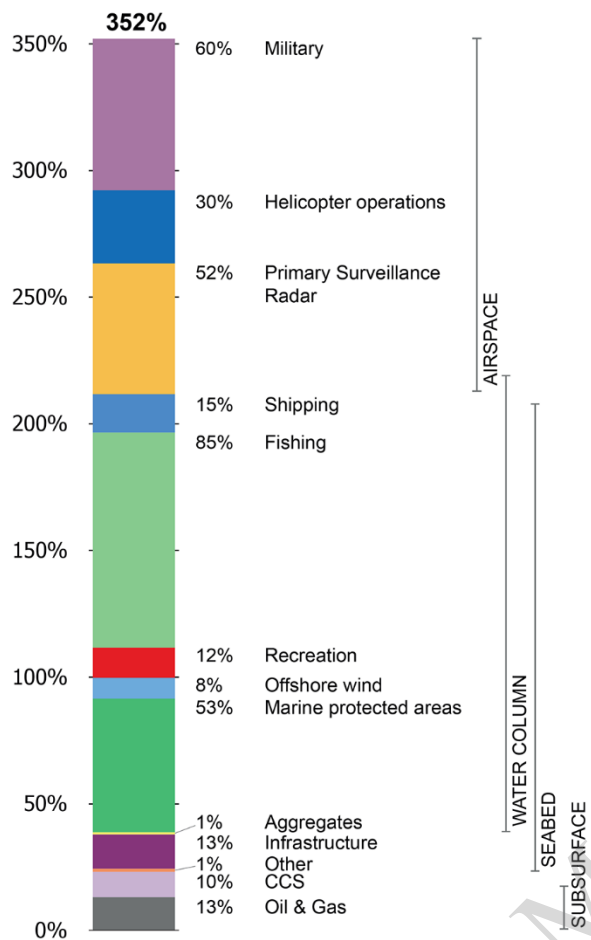


Figure 8

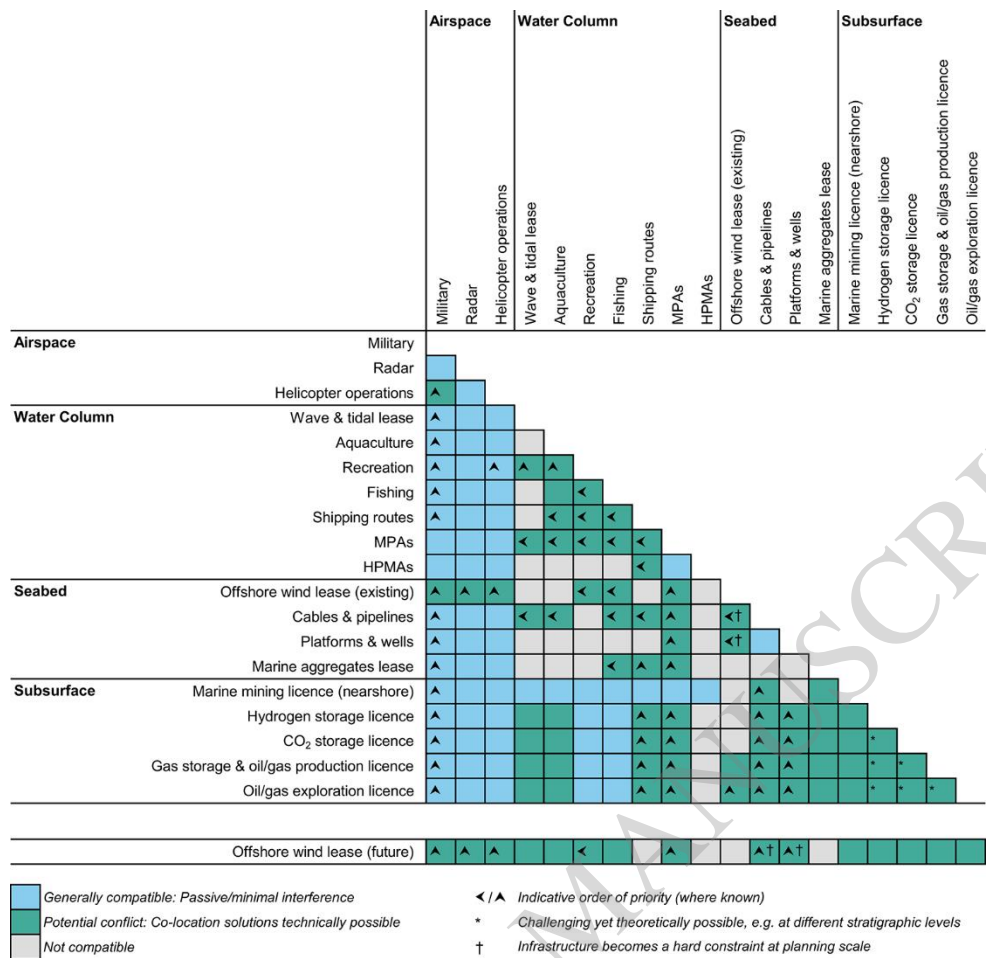


Figure 9

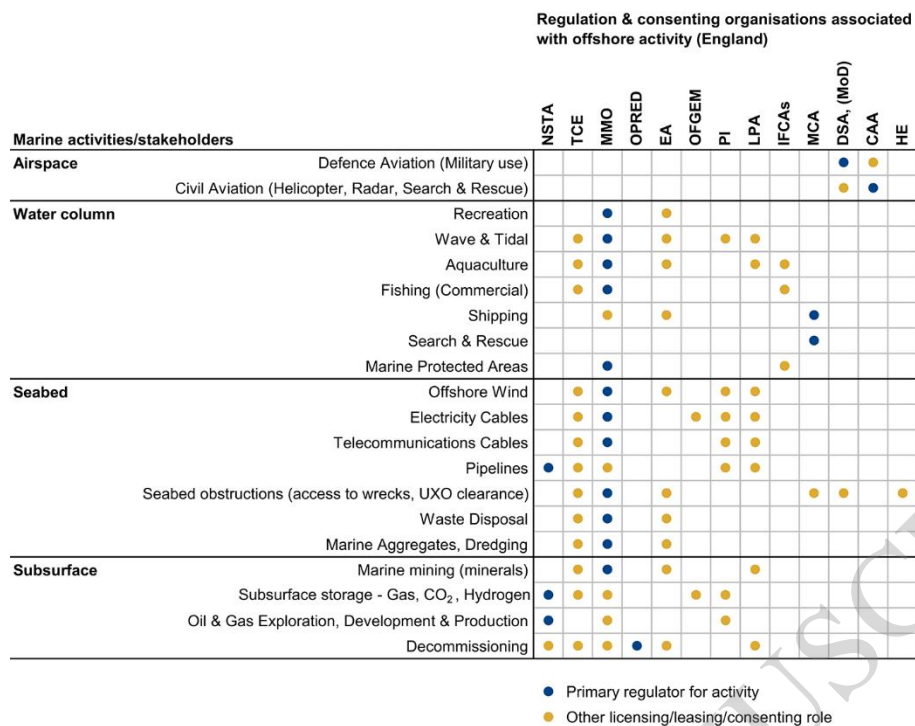


Figure 10

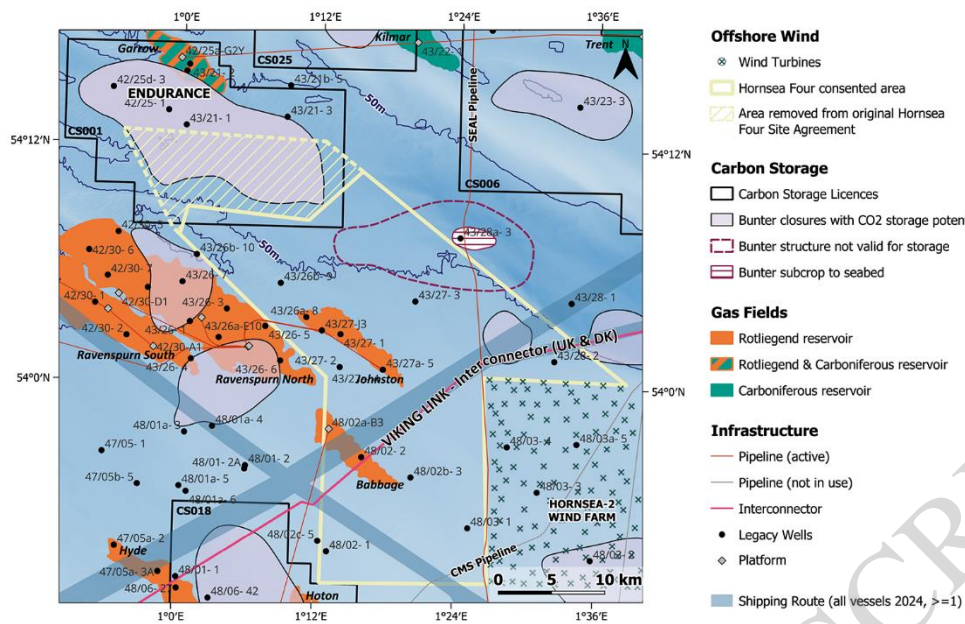


Figure 11

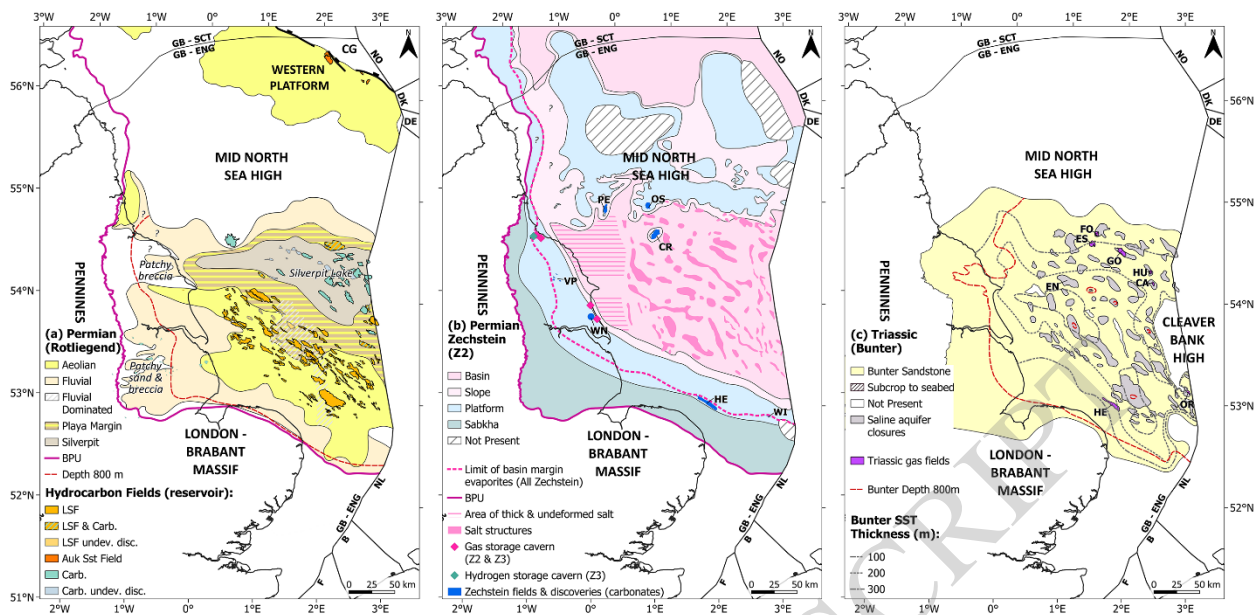


Figure 12

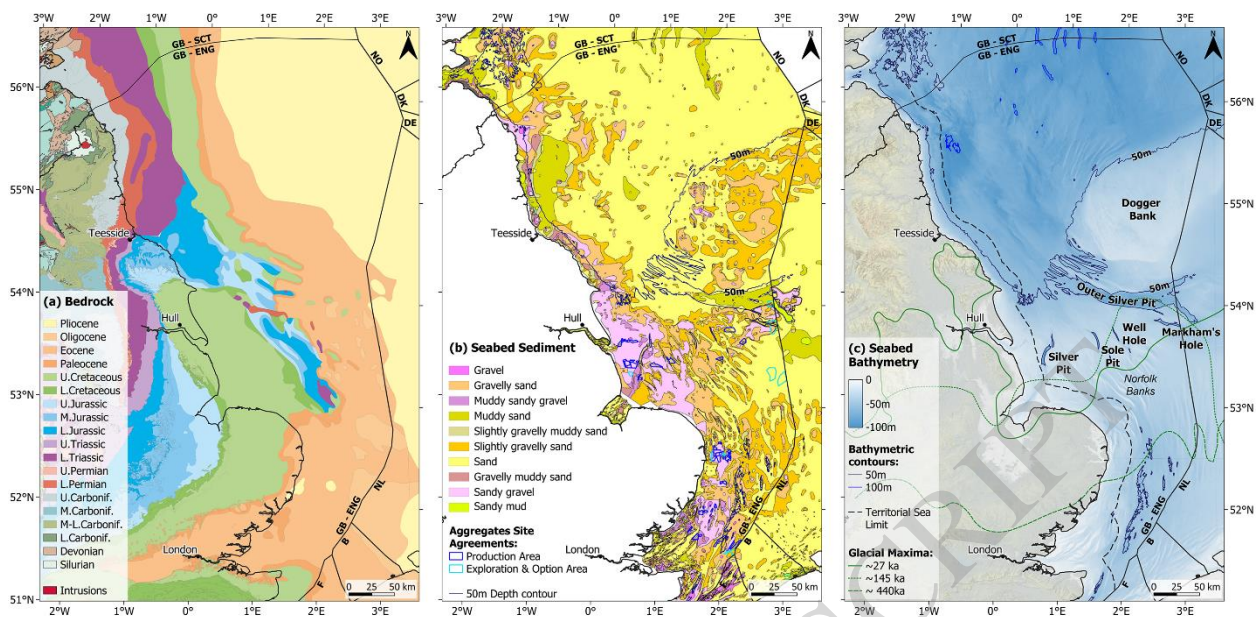


Figure 13

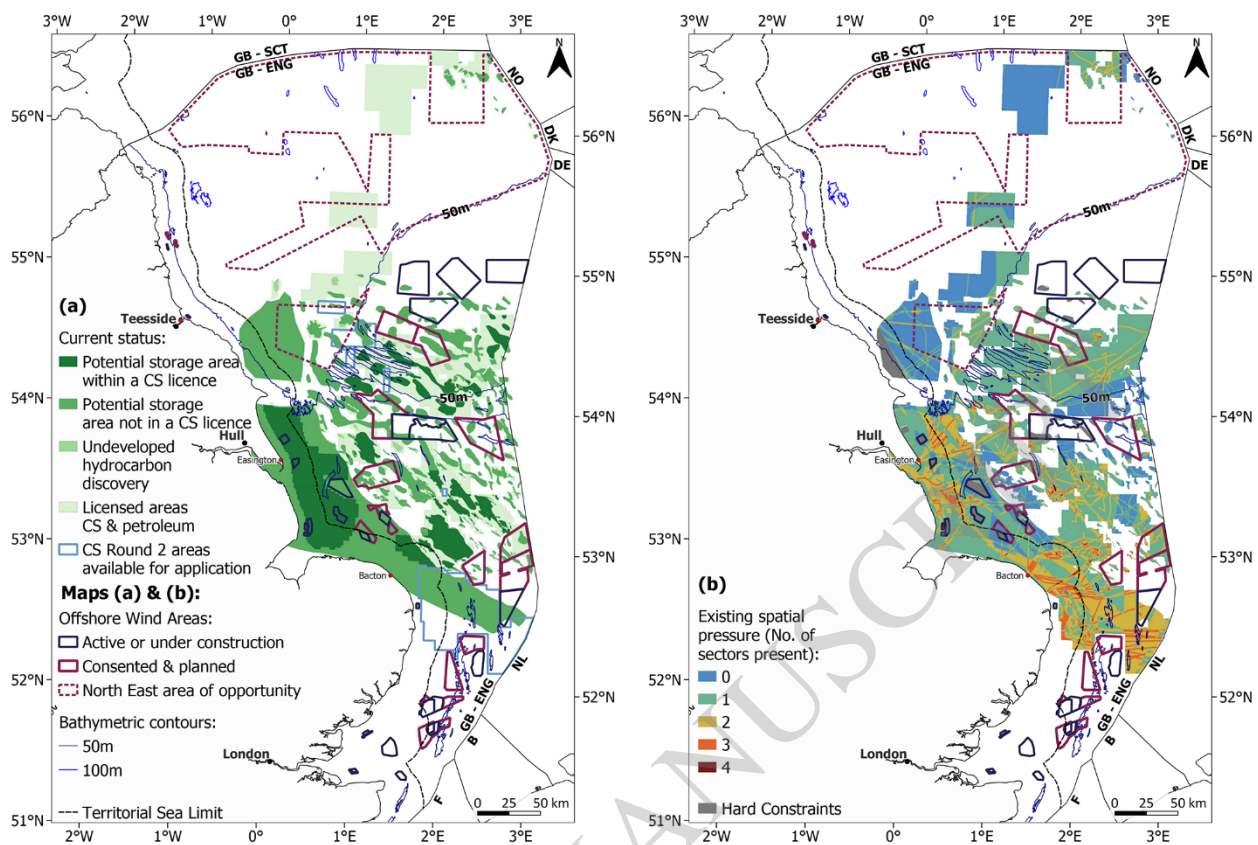


Figure 14

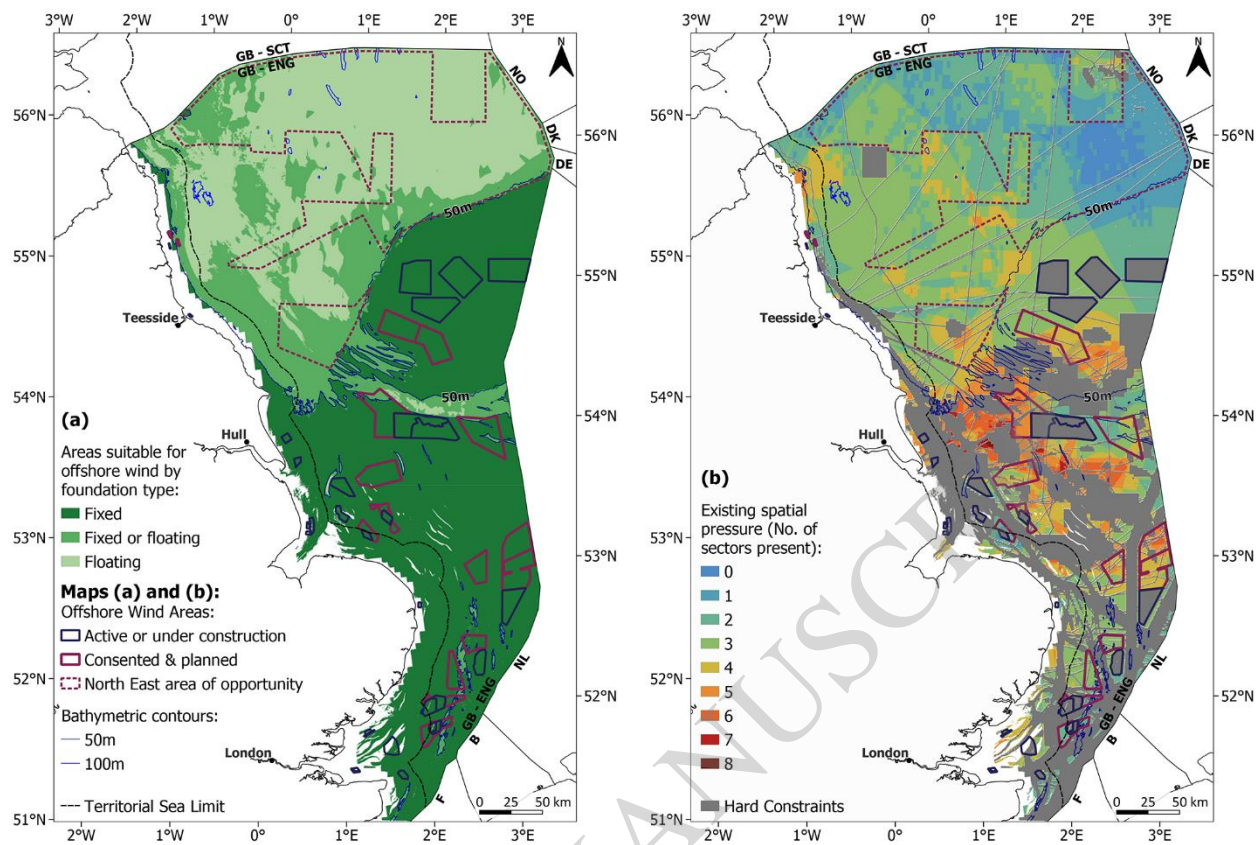


Figure 15

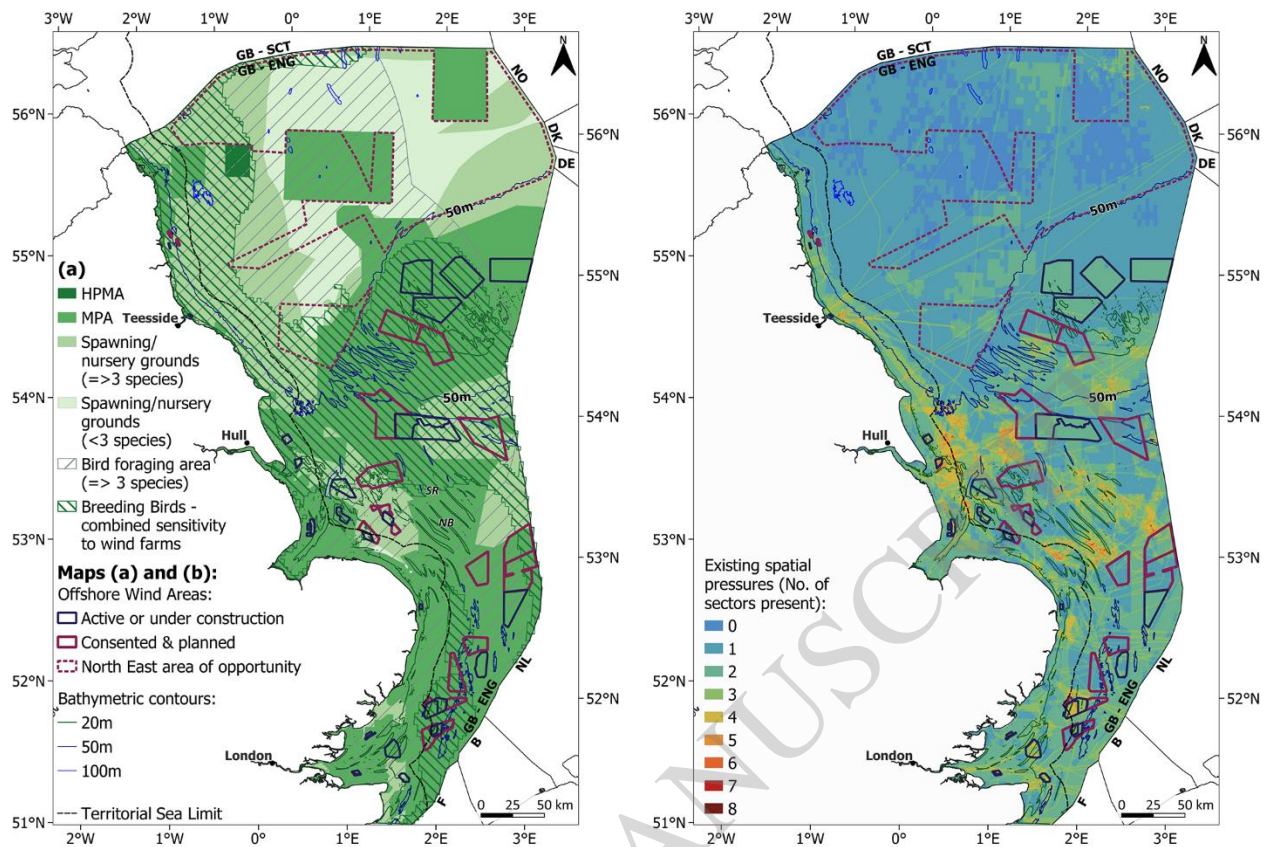


Figure 16

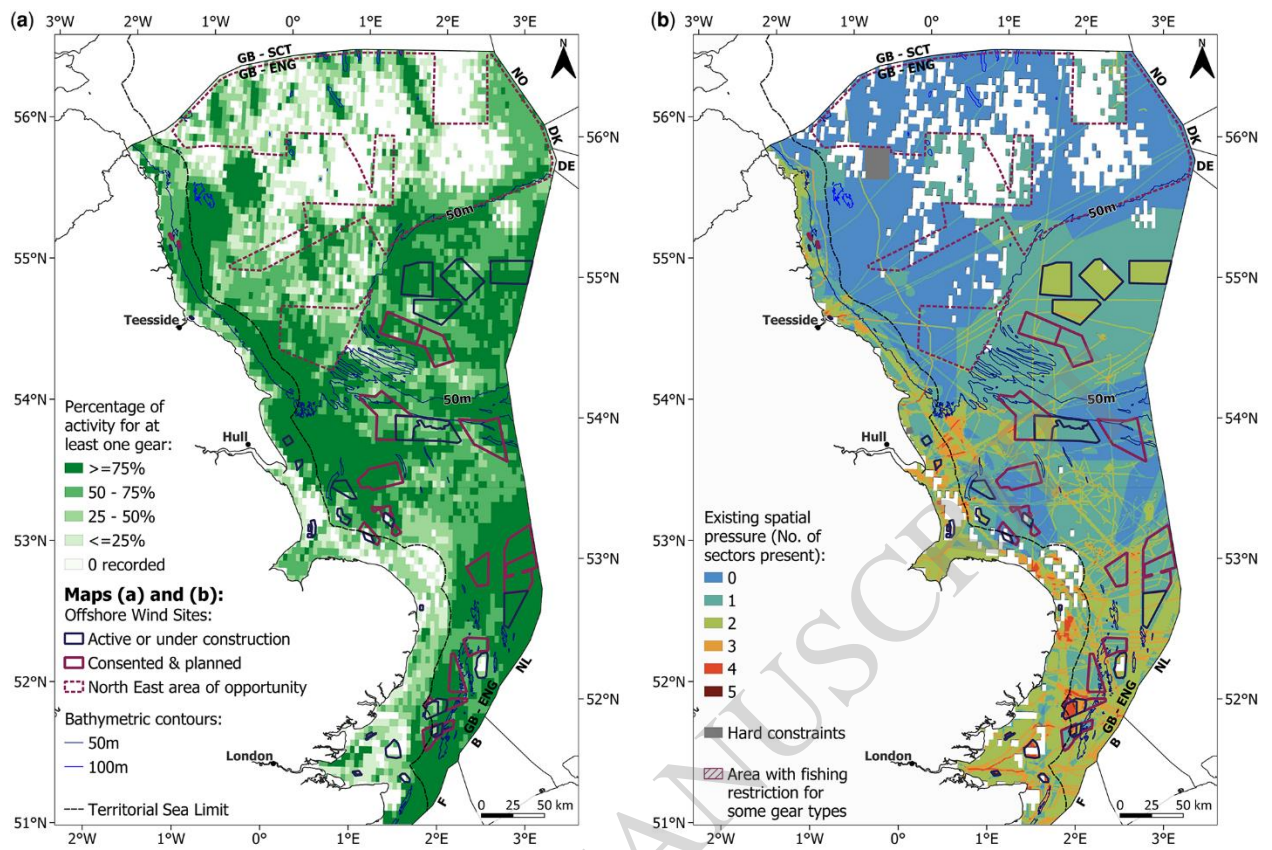


Figure 17

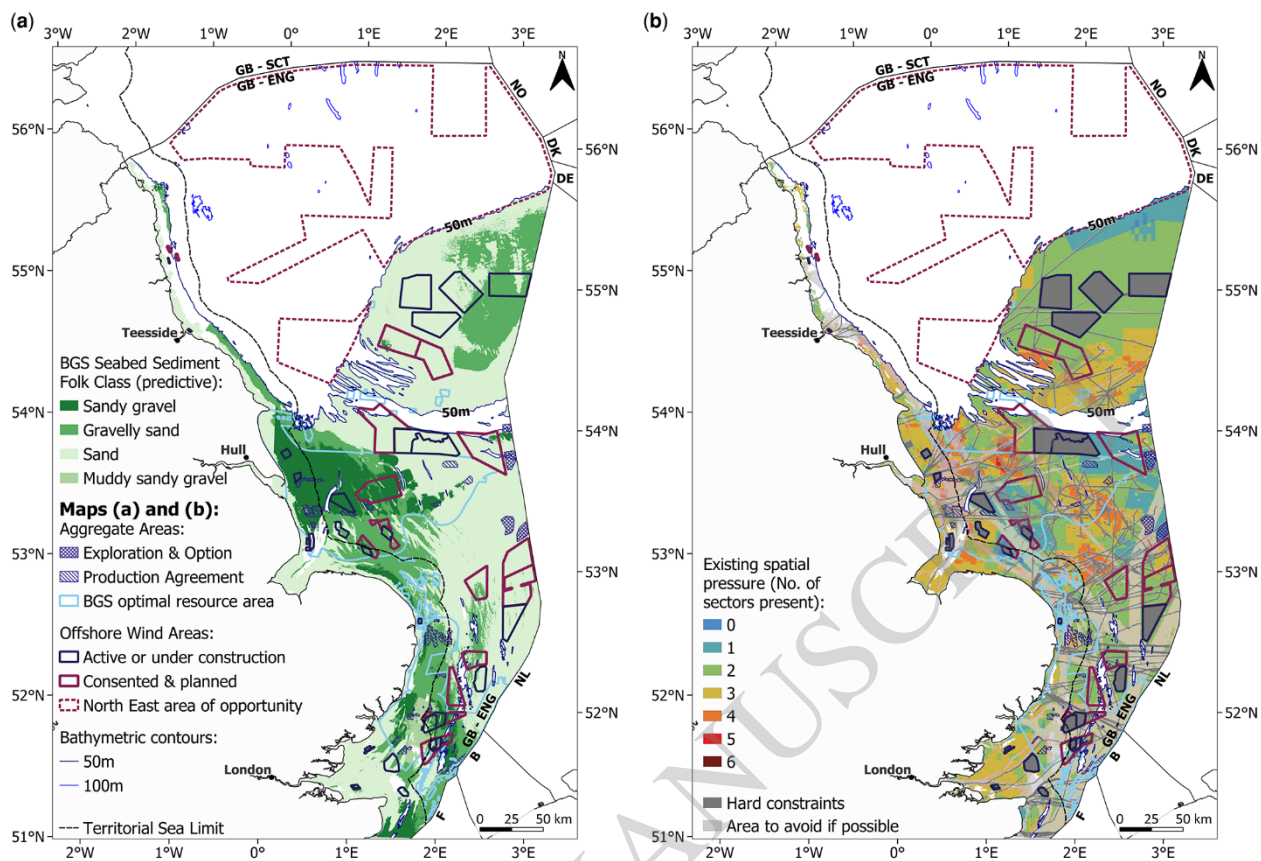


Figure 18

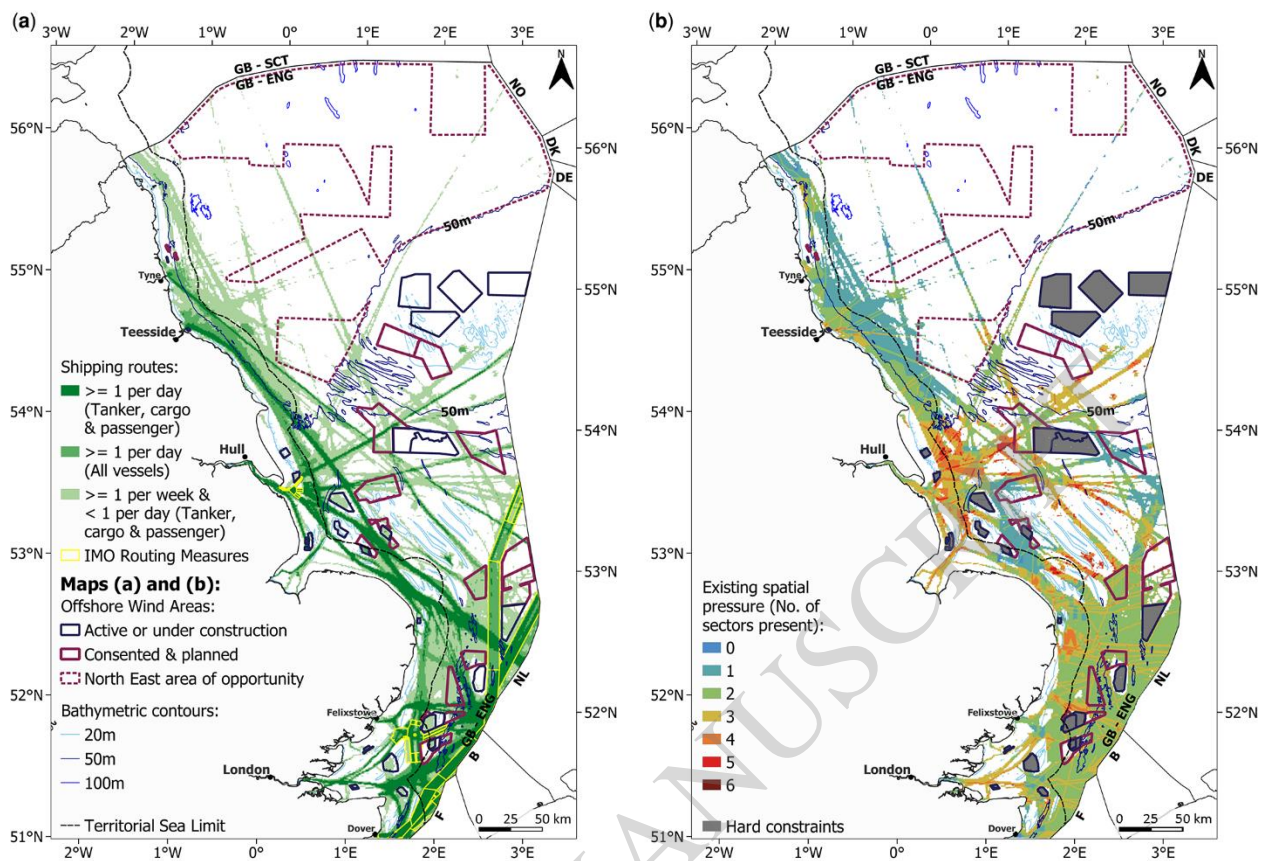


Figure 19

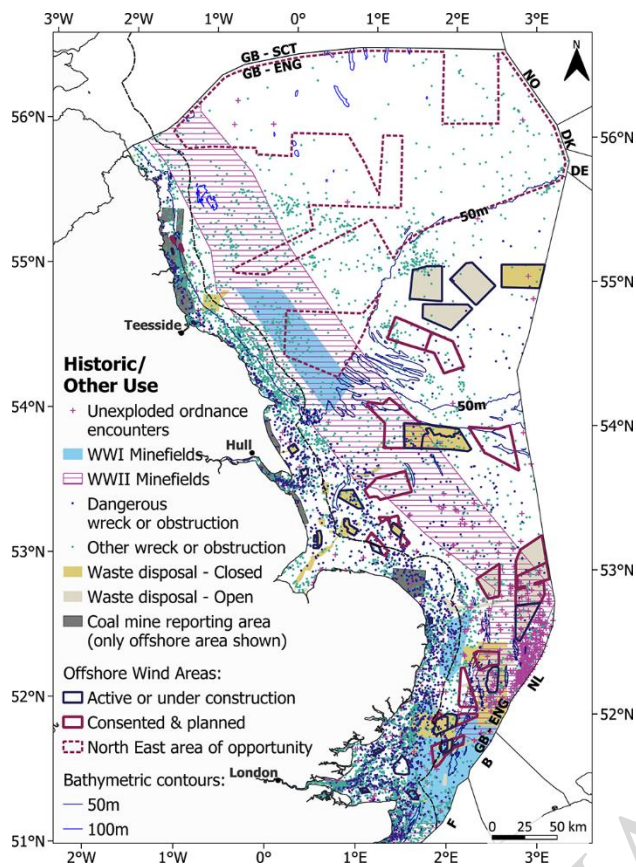


Figure 20

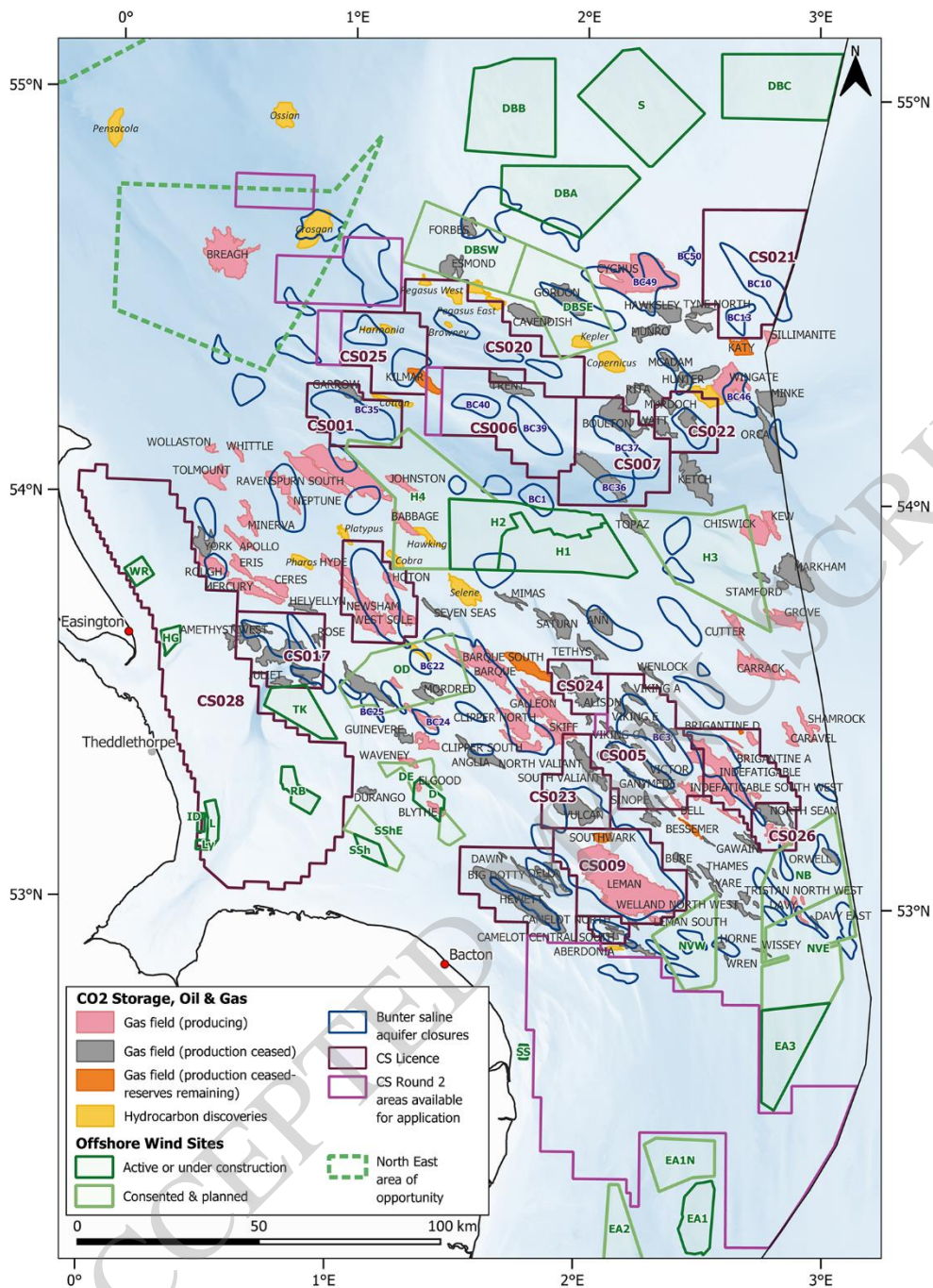


Figure 21

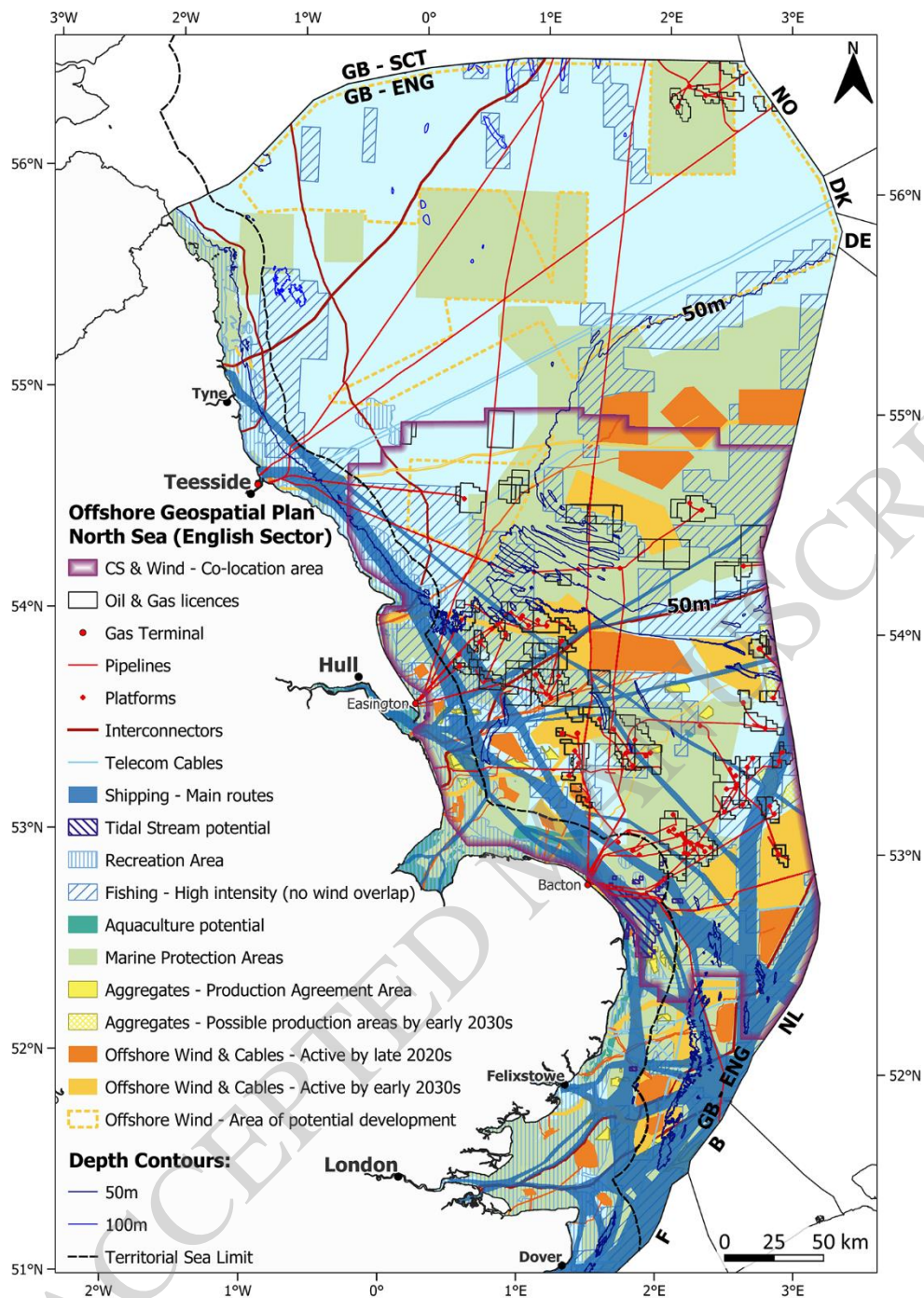


Figure 22

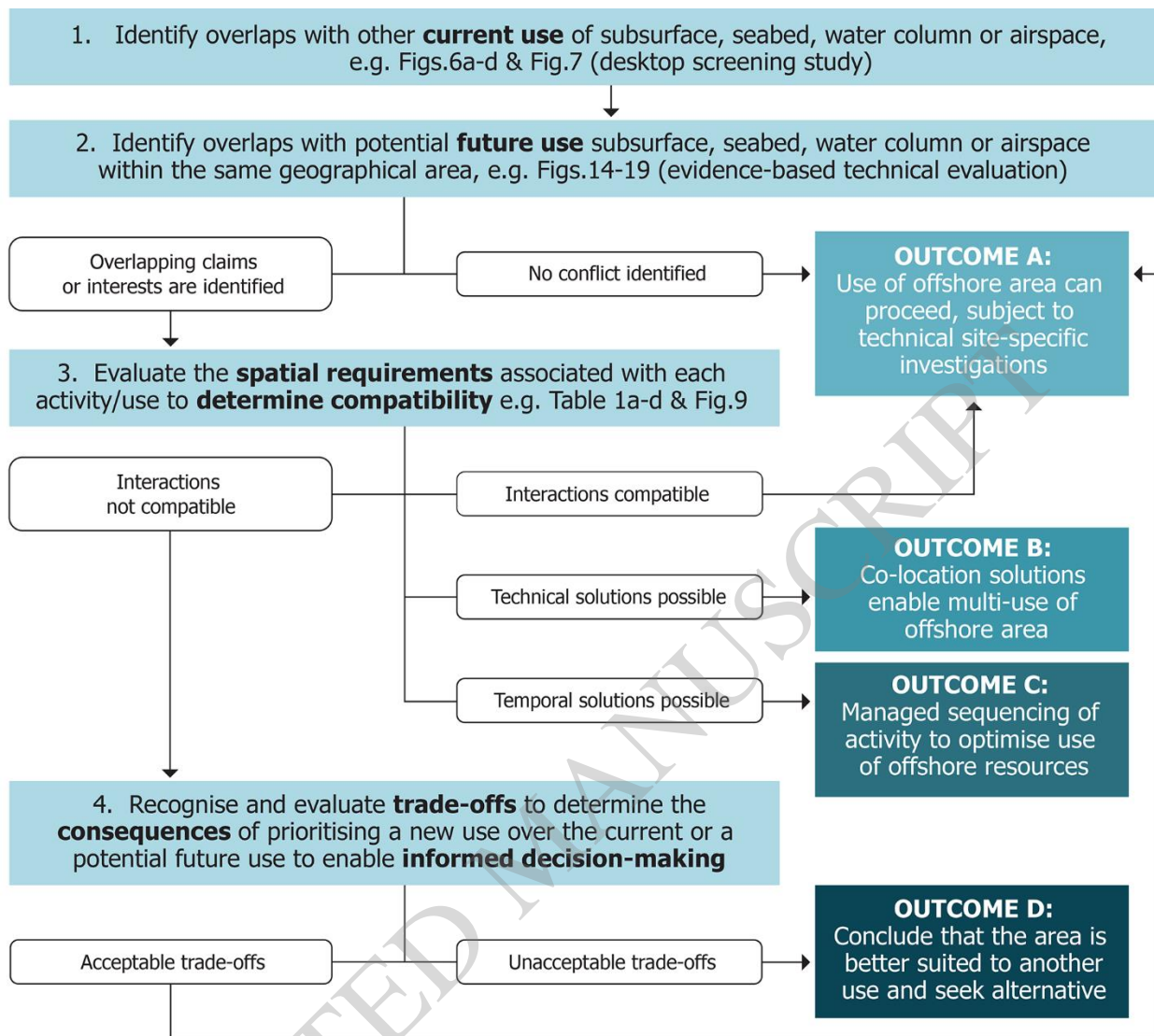


Figure 23