

Article

Offshore Wind and the Spatial Squeeze: A Plausible Future Layout for the North Sea

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Abstract

All of the nations surrounding the North Sea have targets for very large scale offshore wind deployment, and this may have significant implications for oceanography, ecology, and other sea users. Studying these implications is not possible without a plausible scenario for where the wind farms and wind turbines will be located. In this work we produce such a scenario by asking “If all the national ambitions were built, what might the North Sea look like in 2050?” We collate stated national targets and propose a plausible future layout for offshore wind farms. Taking predicted future turbine designs into account, as well as the different wind farm densities planned by each country, we then present a dataset of plausible turbine locations. Our layouts are available as open data for further modelling or analysis. If all national ambitions are fulfilled in 2050, we expect over 19,400 turbines, forming wind farms whose boundaries include approx. 11% of the area of the North Sea. This is very likely to have significant impacts on other sea users, especially fishers, and may have significant oceanographic and ecological effects as well. It will be important for these effects to be studied further, and for policymakers to consider them alongside the benefits of offshore wind expansion.

Keywords: offshore wind; wind farms; North Sea; layout; marine space; marine net gain; marine spatial planning

1. Introduction

Offshore wind power is an important part of European decarbonization. In the UK, it has been described by many as the “backbone” of a future green energy system (e.g., [1,2]). All of the North Sea nations have ambitions for very-large-scale offshore wind deployment, and most of these were increased or brought forward in 2022 following the Russian invasion of Ukraine. For example, in 2019 the UK announced that it would build 30 GW of offshore wind capacity by 2030 [3]. This commitment was later increased to 40 GW [4] and then 50 GW [5], while the Committee on Climate Change anticipated 65–125 GW by 2050 in their Sixth Carbon Budget ([6], p. 25). In the 2022 Esbjerg Declaration, the leaders of Denmark, Belgium, The Netherlands and Germany resolved to “jointly develop The North Sea as a Green Power Plant of Europe” [7]. The remaining North Sea nations joined them for the Ostend Declaration the following year [8].



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These very-large-scale deployments will occupy significant fractions of their nations' EEZs and of the North Sea as a whole. This may have implications for physical and ecological processes below the waterline [9–16] and climatic and ornithological ones above it [17,18]. Conflicts are possible with human activities including fishing [19], navigation [20], recreation [21], and more. There is an urgent need to understand and project these impacts with respect to climate change, ecosystem services [22], decommissioning decisions, fisheries management, and windfarm expansion. To enable this, it is essential to have a plausible layout of future wind farms and wind turbines to form the basis of modelling and analyse, and in this work we aim to address these needs. The locations of wind farms are needed for broad-scale marine planning purposes, while the coordinates of individual turbines are necessary to allow for simulations which take account of hydrodynamics, hard substrate footprints, etc., as well as human activities such as fishing, for which the spacing between turbines is important.

Jongbloed et al. [23] provided an early (2014) view of the potential allocation of space between sea users in the North Sea, based on a comprehensive view of non-energy uses. However, this work was conducted before the scale of offshore wind ambition became apparent, and it considered wind farms purely in terms of sea area, without considering the associated generating capacity. Gusatu et al. [24] provide a more recent look, starting from the available space and considering the installed capacity of offshore wind that might be possible, again under different scenarios of priority between sea users. They concluded firmly that the sharing of space will be important due to its scarcity, and hence emphasised the importance of integrated rather than sectoral planning. Other studies have been commissioned to study specific EEZs in detail (e.g., [25,26] for the UK), but while these are rigorous within their scopes, each is limited to a single country's EEZ and does not present a holistic view of the North Sea.

Our objective is to provide plausible layouts for offshore wind farms, and individual turbine locations, for the North Sea in 2050. Whereas Gusatu et al. [24] started from the available space, our starting point is the stated ambitions for the deployed capacity of all the North Sea nations. We collate these ambitions (Section 3) and then develop a possible layout of the zones that this capacity could occupy (Section 5), based on the recent planned deployment densities of the countries in question (Section 4). Having identified these deployment zones, we propose a possible layout for individual turbines (Section 7), taking into account the planned rate of deployment and the industry's estimates of how turbine sizes—and hence spacings—will increase over time (Section 6). To our knowledge, this is the first attempt at projecting future wind turbine coordinates for the whole North Sea.

The North Sea will be one of the first areas to experience these demands on space, and the potential for increased conflict that may result. This is because it is one of the most densely used bodies of water in the world [23], and because the surrounding nations are early movers in offshore wind. However, the issues discussed are globally relevant and will apply, with variations, to many parts of the world over time.

A Note on Data Versions

This work was originally begun in 2020, and then updated in 2022–2023 to account for increases in most countries' ambitions resulting from the Russian invasion of Ukraine. Outputs based on the situation in 2022 were made publicly available in 2023 and presented at conferences. In the summer of 2024, a revision was undertaken with updated information and some improved methods, especially relating to wind farm densities. This 2024 update should be considered the primary output and subject of this paper, but the 2023 version will sometimes be referenced below for comparative purposes.

National targets and related policies are, of course, a moving target, and so the reader should be aware that things may have changed since the summer of 2024.

2. Description of the North Sea

The North Sea is situated on the North–West European continental shelf and measures approximately 1000 km from North to South and 200–500 km from East to West. Within this area are all or part of the EEZs of seven countries: Norway, Denmark, Germany, The Netherlands, Belgium, France, and the UK (Figure 1).

All of the dominant types of seabed substrate in the North Sea [27] are suitable for offshore wind development, with appropriate foundation types. Spatial variation in mean wind speeds [28] was judged to be minor enough to disregard for this work. The wave environment does vary with latitude in that the northern part of the Sea experiences higher waves [29], making southern sites more desirable for installation and maintenance activities.

The bathymetry of the North Sea is of note: the southern half averages less than 40 m, while north of a line between the Yorkshire coast and the Skagerrak, the depth increases substantially (Figure 1). This will influence the suitability of fixed versus floating turbines by location, as fixed bases have a maximum economic water depth while floating foundations need a minimum amount of water. The deepest part of the Sea is the Norwegian Trench, which reaches 878 m in some areas close to the coast.

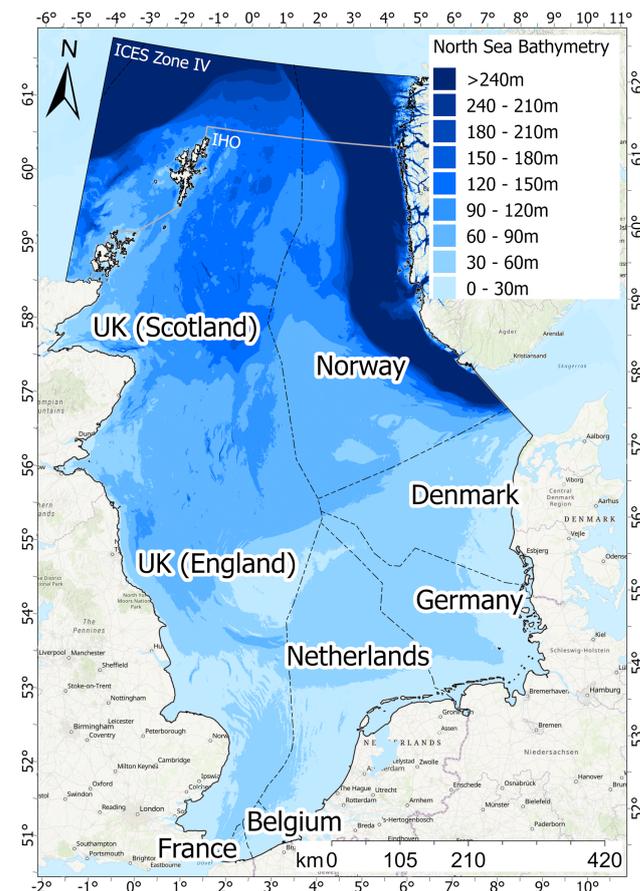


Figure 1. Map of the North Sea showing the boundaries adopted, the bathymetry, and the seven EEZs in this area. The colour scale is truncated at the deep end to allow for detail in the majority of the region.

Boundaries of the North Sea

In setting the limits of the area under consideration, we worked to two definitions. Initially, we adopted the International Hydrographic Organisation (IHO) boundaries [30],

covering approximately the Dover Strait in the south, Orkney and Shetland in the north-west, the 61° N parallel in the north, and the entrance to the Skagerrak in the east. This is the recognised definition that we consider most closely aligned with what an average person—or a politician announcing a national ambition—would consider to be “the North Sea”, and it was the boundary used for the 2023 version of our dataset. However, users of our outputs may be working to a broader definition, and so we also included ICES Statistical Area 4 [31]. This has similar southern and eastern boundaries to the IHO area but is substantially larger in the North and North-West (Figure 1).

In practice, only a very small number of wind farms lie within the ICES limits but without the IHO ones. Our maps and datasets use the larger ICES area, with the limits of the IHO zone marked on the maps. Statistics are provided for both extents. Where wind farms cross the boundary, for statistical purposes, the area lying within the boundary is considered, but on maps and datasets the whole farm is included in order to give users of the data the ability to make their own choice.

3. National Ambitions

The published ambitions for the offshore wind capacity of all North Sea nations were collated. The results of this exercise are shown in Table 1. National energy policies are constantly evolving, and our work is based on the situation, to the best of our knowledge, as of July 2024.

Table 1. Summary of national ambitions for North Sea wind as of summer 2024.

Country	Target Capacity (GW)			Source(s)
	2030	2040	2050	
UK	43 ¹		74 ²	[5,6]
Norway	3	30		[8]
Denmark	5.3		35	[8,32]
Germany	26.4		66 ³	[8]
Netherlands	21	50 ⁴	72 ⁴	[8,33]
Belgium	6	8		[8]
France	0.6			[34]
Cumulative Total	62.3	120.3	306.6	

Notes: ¹ The UK has a target of 50 GW by 2030 in its waters. Existing and planned projects will reach this target, and of these 43 GW will be in the North Sea. ² Assumed target; see text for rationale. ³ Germany has targets for 2035 and for 2045. In this work, we have considered these as as part of the 2040 and 2050 scenarios respectively. ⁴ The Dutch ambitions for 2040 and 2050 are described as “if feasible considering physical space, ecological impact and sufficient demand”.

Countries’ target dates generally fall in the years 2030, 2040, and 2050, and so it is these years that we modelled. Germany has targets for 2035 and 2045 instead of 2050. These “intermediate” targets were considered in our working, but are not shown separately.

Where a country has (for example) 2030 and 2050 targets but no figure for 2040, we assumed a linear interpolation.

The UK has no formal targets beyond 2030, but the existing development pipeline goes well beyond that date. Credible suggested targets for 2050 range from 65 GW to 125 GW [6]. We adopted a central figure of 95 GW, and estimated that 74 GW of this will be in the North Sea (see below).

All of the North Sea (NS) nations except for Belgium and the Netherlands have waters both within and outside the area under consideration. France has only a small portion of its EEZ within the NS, and hence has no specific target for NS deployment. It does plan a single 600 MW wind farm in this area [34], and we assumed that this will be the extent of French ambitions in our area of interest. Denmark and Germany have announced specific

targets for the capacity that they expect to install in the NS versus the Baltic [8], so we adopted these.

Norway has designated many search zones along its full west and north coastline, from the North Sea to the Arctic. As these search zones greatly exceed the area that it would need to build its stated ambitions, we assumed that development will start in the south due to the less challenging metocean conditions and proximity to major ports and population. This aligns with the currently known active developments, and with historical projections [35]. As such, we assumed that all Norwegian OSW development to 2050 will occur within the studied area.

The UK's targets do not specify how much of the capacity will be in the North Sea and how much will be elsewhere. Most UK OSW construction to date has been in the NS, with some small developments along the Celtic Sea coast. However, this was during an era when shallow water was required, and is unlikely to provide a good guide to a future with (as the plans currently assume) extensive use of floating technology. The locations of all the likely UK development until 2030, and much of that to 2040, is already known and planned. For further construction beyond this, we took the ratio of capacity in the NS vs elsewhere in the sum of the Round 4, Round 5, and ScotWind leasing rounds—all of which were determined after floating wind became available—and assumed that the same ratio will apply.

4. Wind Farm Power Densities

For the earlier 2023 version of our dataset, we assumed that all wind farms would use a turbine spacing of seven rotor diameters, as this was a typical spacing found in the literature [36,37]. This gave densities of installed capacity of 5–6 MW/km². As part of the 2024 update, we noted that different countries are using radically different densities in their planning and recent construction. Therefore, for each country, we established a target density to use when designating new zones, or for any planned zones for which the size and capacity were not yet known. These are shown in Table 2.

Table 2. Target densities of the installed capacity used for each country's EEZ.

Country	Density (MW/km ²)	Rationale
UK	3.48	Based on a sample of recent and near-future planned sites. Some older farms have higher densities.
Norway	2.86	Based on wind farm areas and capacities at recent auctions for sites (Sørige Nordsjø II & Utsira).
Denmark	4.50	From an assumption stated in a 2022 report by the Danish Energy Agency [38].
Germany	12.71	Average density of planned wind farms to 2040 [39].
Netherlands	5.76	Average of densities of developments proposed for Dutch 2030 targets.
Belgium	10.98	From existing and planned farms in the Princess Elizabeth Zone.
France	5.04	Density of planned Dunkirk wind farm (only one in French North Sea sector).

5. Zones for Offshore Wind

5.1. Method

Having established the ambitions of each nation, an analysis of existing and planned offshore wind capacity was performed. In most cases this was sufficient to reach the 2030 targets, and in some countries it could reach much further. It was assumed that any existing wind farms that reached their end of life before 2050 would be repowered in place with the same layout and capacity. This is an unrealistic assumption but it is a useful simplification, and because older wind farms are much smaller than recent and future ones, it will have little effect on the results. Note that, in a first approximation, repowering over

the same farm area with larger turbines will cause only small changes in the total capacity, because larger turbines are spaced further apart.

The wind farms planned under the UK's Innovation and Targeted Oil and Gas (INTOG) leasing round, which will be used to power offshore platforms and will not connect to onshore electricity grids, are included on our maps but were not counted towards the national capacity targets. The same approach was applied to the Hywind Tampen wind farm in the Norwegian sector, which supplies only nearby oil fields.

After existing planned developments were exhausted, the further wind farms required to meet the new capacity required by each date were first placed in existing designated areas for offshore wind deployment. The extents of these zones were sourced from publically available information such as national marine spatial plans. Figure 2 shows the areas that were thus identified.

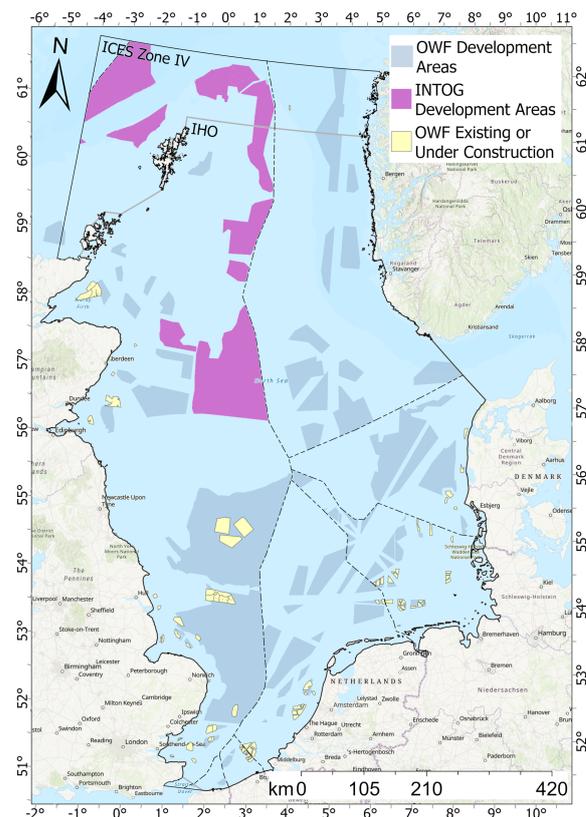


Figure 2. Map showing existing designated areas for offshore wind development (blue), as well as existing and under-construction wind farms within them (yellow). INTOG and similar zones are shown in red. For data sources, see Appendix A.

After existing designated areas were exhausted, further capacity was placed so as to avoid the following areas as far as possible:

- Designations for nature conservation.
- Customary but uncoded shipping routes, identified from AIS-sourced traffic density maps.
- 12 NM from shore.
- Nationally designated shipping lanes.
- *IMO-designated shipping lanes and vessel separation schemes.*
- *Existing physical infrastructure including existing offshore wind, oil and gas facilities, pipelines, etc.*

Shallow water was preferred over deep water where available.

The last two items, shown in italics, were considered absolute exclusions and never used for offshore wind, with one exception: where a single, simple, pipeline or cable ran through a prospective wind farm, this was allowed, on the basis that its 500 m exclusion zone could be avoided by the micrositing of turbines. There is evidence of this occurring with existing wind farms, and future farms will have wider turbine spacings.

Where customary shipping routes were blocked by new wind farm zones, alternative routes were left clear to limit the amount of diversion required for vessels. Where it was necessary to encroach into one of the zones listed above to meet targets, an attempt was made to follow the same priorities that we could observe in existing nationally designated development areas. For example, Denmark appears to strongly avoid areas designated for nature conservation, and so we followed the same approach. Meanwhile England has placed wind farms within nature areas, but in recent developments has avoided the 12 NM limit. We lacked the resources within this small project to fully understand the planning policies of each nation, so we acknowledge that our observations of their priorities may be incomplete. Ultimately, the final decisions regarding the placement of future wind farms are down to human judgement.

The specific rationales for the placement of new zones varied by EEZ, as follows:

Norway: The 2030 target is reached by projects that have been awarded and tendered projects that have not yet been awarded. After this, we used the designated areas scheduled to be opened next, followed by areas in the south of the EEZ where wind farms were historically planned but never built.

Denmark: The 2030 target is satisfied by the Horns Rev 3 project. Zones for 2040 and 2050 were placed within the designated search area for wind farms, while leaving space for shipping and infrastructure exclusions.

Germany: Germany has extensive plans for OSW development and has already zoned its EEZ accordingly. Only a small additional area was required to meet the 2050 targets at the high density that is planned.

Netherlands: Dutch plans for wind farm locations to 2030 are clear, but after this the zones are speculative. The target for 2040 fits within the existing designated search areas, but the 2050 target would greatly exceed this. New zones have been placed to avoid infrastructure, especially IMO shipping lanes, and minimise distance from shore. A choice was made to place some wind farms within an environmentally designated area, as alternative locations would be much further from land. It is possible that, if a similar choice is faced by the Dutch authorities in the future, a different decision may be reached.

Belgium: Belgian plans may be optimistic within the space that they have available. The planned zones will provide around 6 GW of capacity at the high density planned, but to achieve the full 8 GW that is intended for 2040, it was necessary to add a zone within a marine protected area (MPA). We note that there are already designated zones for sand extraction and other “commercial and industrial activity” within the MPA [40], and our proposed wind farm overlaps with these.

France: France has a single wind farm planned in the North Sea, and we assumed that there will be no others in the very limited space available.

UK: The UK already has the largest installed capacity of the North Sea nations, and also a great deal in the “pipeline”. Developments that are already planned will exceed the 2030 targets and meet most of our assumed target for 2040. Small areas were added in both England and Scotland to meet our assumed target for 2050, using additional parts of the Round 4 and ScotWind search areas, respectively.

5.2. Results

Our layouts for the target years 2030, 2040 and 2050 are shown in Figures 3 and 4. We emphasise that these layouts should not be seen as *predictions*—for they will certainly be wrong in at least the detail—but rather as *plausible* scenarios which can be used as a basis for further analysis. Table 3 shows the sea area occupied by wind farms in total and in each EEZ, both as an absolute area and as a proportion of that EEZ. The proportion of the North Sea that is projected to lie within the boundaries of a wind farm is 11.1% or 9.7% for IHO and ICES boundaries, respectively.

Table 3. Areas of wind farm in each EEZ, and the proportion of the part of that EEZ within the North Sea that they enclose, in the 2050 projection. The “Whole NS” row shows the total area of all projected wind farms that lies within the chosen North Sea boundaries, and the proportion of the whole North Sea that they enclose.

EEZ	Wind Farm Area in IHO Zone		Wind Farm Area in ICES Zone	
	km ²	% of EEZ	km ²	% of EEZ
UK	22,104	8.9	22,172	7.2
Norway	9852	8.2	10,519	7.5
Denmark	7997	16.1	7997	15.4
Germany	5636	13.6	5636	13.6
Netherlands	12,139	18.9	12,139	18.9
Belgium	629	17.8	629	17.8
France	119	6.8	119	6.3
Whole NS	58,476	11.1	59,211	9.7

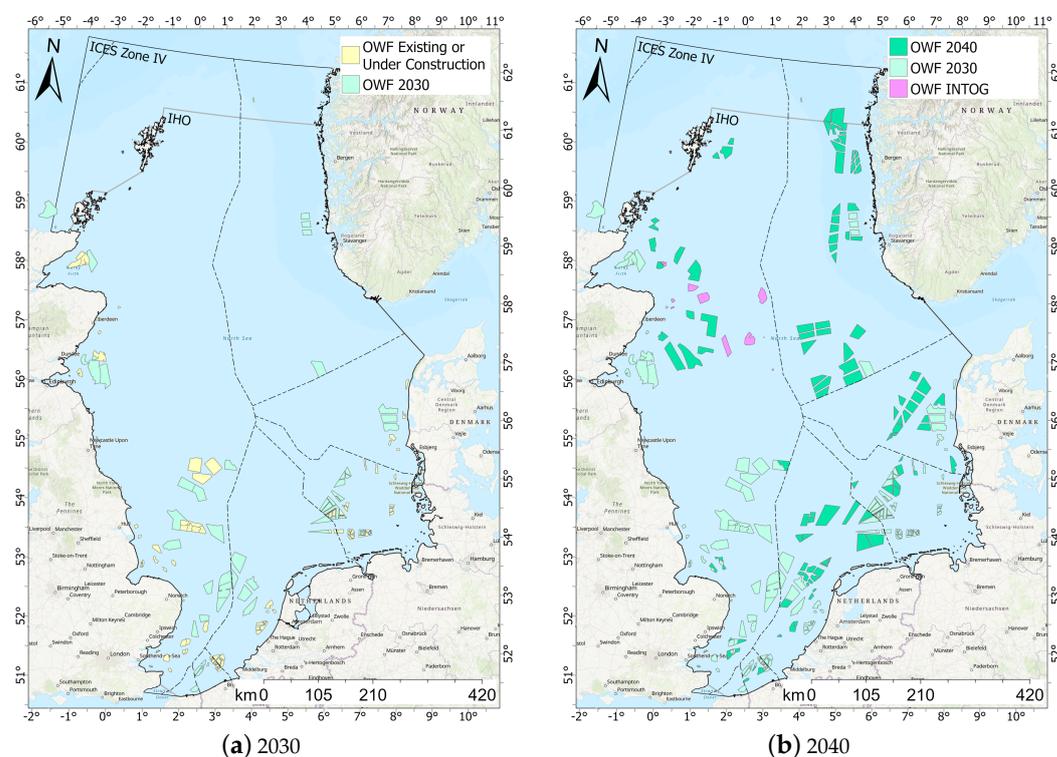


Figure 3. Maps showing plausible arrangements of offshore wind farms in the North Sea in 2030 (a) and 2040 (b). Dashed lines show EEZ boundaries. Existing wind farms, shown in yellow on the 2030 map, are included within the “2030” category on the 2040 map.

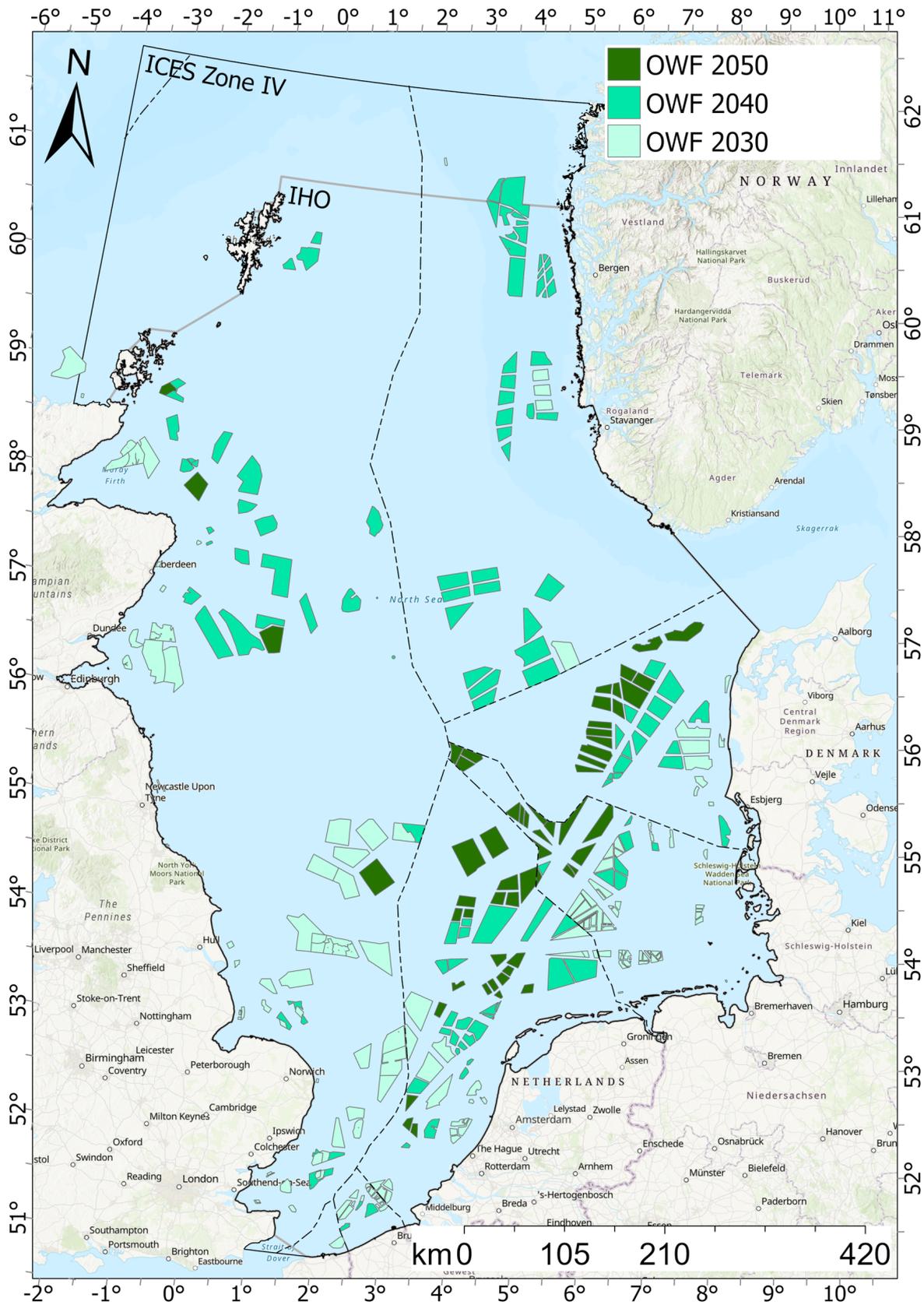


Figure 4. Map showing a plausible arrangement of offshore wind farms in the North Sea in 2050. Dashed lines show EEZ boundaries. INTOG wind farms, shown separately in Figure 3b, are included in the “2040” category here.

6. Future Wind Turbine Capabilities

The deployment zones and turbine layouts presented in this work represent offshore wind construction over a period of decades. During this time, wind turbine power and diameter, and hence the spacing between turbines, have already changed and are expected to change further.

Predictions have been made that offshore wind turbines will be deployed with 17–20 MW capacity by 2035 [41,42] and 24 MW by 2040 [25].

In order to assess how confident we should be in these predictions, a dataset of historical, current and prototype models was assembled. Historic information was obtained from The Wind Power, current designs from manufacturer websites, and future predictions from the sources above. Figure 5 shows the rated capacities and diameters of these turbine designs over time. From these visualisations, we concluded that the industry projections of future turbine power and diameter were plausible, and hence could be adopted for this project.

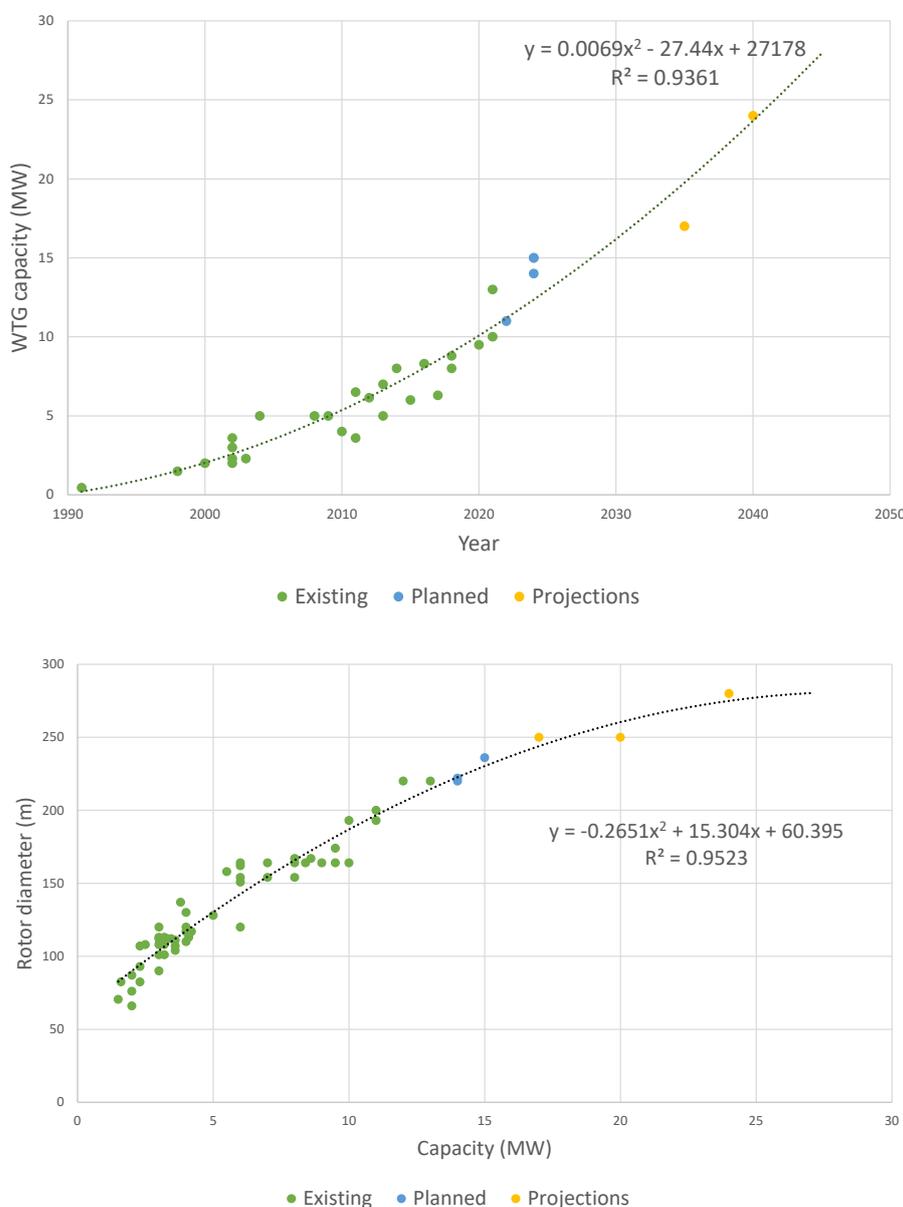


Figure 5. Plots showing the progression of wind turbine capacities and diameters over time. Data sources as per text.

A set of generic turbine specifications was produced, shown in Table 4, for both fixed and floating foundations. The specific types of foundations (e.g., monopile or jacket, semi-submersible or spar buoy) are not important for this work as they do not affect the turbine spacing or the density of installed power.

For existing wind farms and those where the technology that is to be used is known (e.g., a tender has been awarded to a manufacturer) we used the real specifications in our work. For future wind farms, and for planned farms without clear information, we used these generic designs. It was assumed that fixed foundations would be considered in water depths of less than 65 m, and that floating foundations could be used in depths greater than 45 m. Between these depths, judgement was applied regarding the specific situation of that wind farm.

Table 4. Generic turbine specifications adopted for this work.

Foundation	Year	Capacity (MW)	Diameter (m)
Fixed	2030	15	236
Fixed	2040	17	250
Fixed	2050	27	300
Floating	2030	12	220
Floating	2040	17	250
Floating	2050	27	300

7. Possible Turbine Layouts

7.1. Method

Following our allocation of zones for offshore wind development, we developed a plausible set of coordinates for turbine locations. For existing wind farms and those under construction whose layouts were known, turbine locations were drawn from a published dataset by Martins et al. [43] (described in [44]).

For new wind farms, a square grid was generated, aligned to the south-westerly prevailing wind direction. The spacing to be used was calculated for each zone using the density practiced by that country (Table 2) and the expected turbine capacity, either from known specifications or from the generic turbines in Table 4. The origin point of the grid was nudged, where useful, to fit the maximum number of turbines in the zones. However, no attempt was made at micro-siting or other optimisations; such an exercise would be impractical without detailed surveys of each location, and would offer little benefit for a hypothetical layout such as this.

7.2. Results

Figure 6 shows an example of the population of the zones with turbine locations; in this case, in the Belgian EEZ. A total of 19,573 turbines were positioned within the North Sea boundaries across the zones identified in Section 5.2. These are detailed in Table 5.

Our output dataset includes an additional 123 turbines that are not within the ICES North Sea, but are within wind farms that partially intersect the North Sea—thus, our turbine locations dataset includes a total of 19,696 locations.

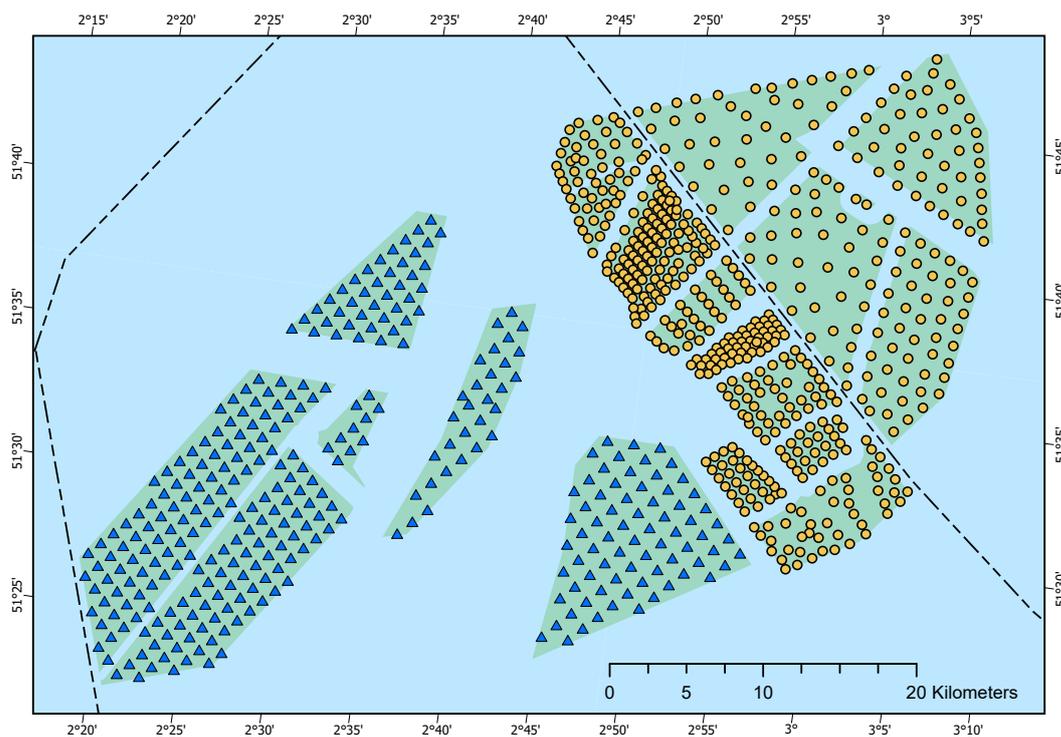


Figure 6. Example map showing the projected offshore wind zones populated with turbine locations in parts of the Belgian and Dutch EEZs. Yellow circles represent known turbine locations from the Martins et al. [43]. dataset, while blue triangles use a grid generated at the density in MW/km² planned by Belgium. Dashed lines are EEZ boundaries.

Table 5. Cumulative quantity of turbines within the IHO and ICES boundaries in 2030, 2040, and 2050.

EEZ	IHO Zone			ICES Zone		
	2030	2040	2050	2030	2040	2050
UK	4272	6072	6306	4291	6091	6325
Norway	200	1694	1694	211	1847	1847
Denmark	538	1411	1975	538	1411	1975
Germany	2687	3240	4348	2687	3240	4348
Netherlands	1735	3459	4292	1735	3459	4292
Belgium	627	745	745	627	745	745
France	41	41	41	41	41	41
Whole NS	10,100	16,662	19,401	10,130	16,834	19,573

8. Discussion

8.1. Assumptions and Sensitivities

We followed the stated intentions of governments and made no attempt to assess whether they are feasible in terms of economics, politics, supply chains, etc. This is a limitation of the study. Some of these targets may be aspirational in nature, and if this is the case then it would be wise to treat our projection as an upper bound of the plausible level of deployment.

We specifically highlight a sensitivity to the readiness of floating offshore wind. As of summer 2024, this is a young technology: the largest installed floating wind farm is Hywind Tampen, consisting of 11 spar buoys in Norwegian waters [45], and the number of floating wind farms in the world is small. The industry appears confident that floating wind will develop rapidly, evidenced by developers bidding for zones in deep water in the ScotWind programme [46], and in this work we assumed that this will progress as

anticipated. If the large-scale deployment of floating wind proves to be significantly more difficult or expensive, this will have major implications for our analysis, primarily affecting the UK and Norway. In the UK, for targets to be met, we would expect much denser development in the shallower southern part of the EEZ, and less in Scottish waters, while Norway would struggle to reach its stated targets using current bottom-fixed technologies.

There is some sensitivity to the future of currently extant oil and gas structures. Many of these will be decommissioned in the coming decades if they are not converted to use in carbon sequestration operations, and it is not yet clear whether they will be fully or partially removed. However, such infrastructure occupies a relatively small area when compared to the scale of the wind farms in question.

We assumed that offshore wind installations will develop until 2050 with larger versions of the “Danish model”—i.e., three-bladed horizontal-axis turbines. If the industry diverges from this trajectory, it is possible that the alternatives proposed (see e.g., [47] Chapter 6, [48]) would result in different layouts and power densities.

8.2. Density of Installed Power

More generally, our analysis is sensitive to the density of the installed power. It is notable that the countries that will have the most difficulty fitting their stated ambitions into their EEZs, Germany and Belgium, are those that are planning densities 2–3 times greater than their neighbours (Table 2). While these higher densities will fit more capacity into a given area, the energy yield per turbine, and hence the economic efficiency, is likely to be poorer due to increased intra-array effects. This suggests that installed capacity may not be the best metric on which to set targets, but also raises questions about how the optimal spacing for wind turbines might change when space is scarce, and thus developers optimise, not only for MWh/\$ but also for MWh/km².

It is worth noting that the density of installed power is approximately independent of the size of the turbine that is adopted by any given development: because the power of a turbine scales with its swept area, and the spacing between turbines is normally specified as a number of rotor diameters, larger turbines are approximately cancelled out by the increased spacing. Therefore, our projected wind farm zones are not sensitive to errors in our projections of future turbine size. The projected positions for individual turbines would, of course, be affected.

8.3. Implications

As noted in the introduction, the very-large-scale deployments considered here may have implications for oceanographic, ecological, and atmospheric processes. There is a growing body of evidence demonstrating the complex impacts from the construction and operation of wind farms on ecosystems and ecosystem services based on development so far [49,50]. These impacts will vary in their specifics. For example, the construction of fixed turbines involves pile-driving, which is of particular concern regarding its impacts on marine mammals [51], whereas floating wind farms may substitute this hazard with an increased risk of entanglement [52].

Physical oceanographic effects are less well-characterized, and are probably minor (or at least local) so far, but it is clear that there is potential for large-scale impacts. In particular, the additional mixing induced by wind farms may affect seasonal stratification and primary productivity [10,11,13–15]. Such changes are likely to scale non-linearly with the progress of offshore wind development, and would have significant additional effects on ecosystems.

Aerodynamic effects above the waterline are perhaps better understood. Depending on atmospheric conditions, the wakes of wind farms have been observed to reach at least

45 km [53], and when the wake of one wind farm impinges on another, yields will be affected [54,55]. With many large wind farms in close proximity to one another, such interactions appear inevitable, and a number of disputes have already arisen [56]. The transboundary effects are likely to be significant, and the legal situation regarding “wind theft” between neighbouring EEZs is unclear [57]. Holistic regional planning may be beneficial for wind, as it is likely to be for tidal stream energy [58] to minimise wake interactions and take advantage of blockage.

Introducing wind farms occupying 11% of the North Sea will inevitably cause spatial conflicts with other sea users. Industries such as mineral extraction, aquaculture, and oil and gas production (or the carbon sequestration facilities that may replace it in the same geological formations) may be somewhat protected by having designated zones in which to operate [59]. Fishing faces particular challenges as an industry that depends not only on surface space but also, depending on the fishing method, on an unobstructed subsea environment. A body of the literature has already begun to emerge to cover the potential for conflict or the sharing of space (see e.g., Haggett et al. [19]).

Shipping navigation is likely to face less conflict with offshore wind, because it is concerned with a route between points rather than the area of sea surface that is available. However, where vessels must be routed around wind farms, this will increase journey times and/or carbon emissions. There is also potential for increases in navigational risk [20], where vessels must follow extended “lanes” between large wind farms. Different considerations apply for recreational sea users [21] and other small craft; the effect on them will vary greatly between jurisdictions where small boats can navigate freely through wind farms (e.g., the UK) and those that treat the entire farm area as an exclusion zone (e.g., Belgium).

9. Conclusions

According to the layout that we developed, all of the North Sea nations have room for their national ambitions—although Germany and Belgium will only achieve this by installing at very high densities, which will lead to lower capacity factors. The overall proportion of the studied area that we expect to lie within the boundaries of wind farms in 2050 is 11% of the IHO-defined North Sea or 10% of ICES Zone IV, compared to approx. 0.1% in summer 2024. Wind farms are expected to comprise the highest proportion of the Dutch EEZ, at 19% (Table 3). The total number of turbines projected in the North Sea in 2050 is over 19,400, with the greatest numbers in the British, German, and Dutch sectors (Table 5).

Significant impacts are likely, and are almost assured for other sea users, such as fishers who depend on the area of ocean available to them rather than simply on having a path from A to B. It will be important for policymakers to consider these impacts alongside the benefits of offshore wind expansion, and to seek ways to mitigate them.

Understanding the future impacts of offshore wind development will be critical to the realisation of targets surrounding just transition, marine net gain, natural capital, energy security, and climate change. The ability to simulate these effects has previously been limited by the lack of a future wind farm layer providing turbine locations for the whole North Sea—which we present here. We emphasise again that this scenario is not intended as a prediction of where wind farms will be. The layouts presented here reflect the magnitude of offshore wind development that is required to meet the current targets, both at a whole-sea level and by EEZ. They provide plausible locations of wind farms and turbines, which can be used as the basis for the modelling and analysis that is required in order to predict and understand these future impacts.

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Data Availability Statement: Shapefiles showing both wind farm zones and turbine locations, along with a CSV file presenting turbine locations, are available as open and citable datasets on the Zenodo repository. The 2024 version that this publication refers to is available at <https://doi.org/10.5281/zenodo.14222865>. Earlier versions are linked from that page, although we recommend using the current version. In the event of future updates, <https://doi.org/10.5281/zenodo.7109882> will always return the latest version. The data are shared under a Creative Commons Attribution license. We encourage readers to use these datasets for further analysis and modelling, and ask that both the dataset and this paper are cited and acknowledged.

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Appendix A. Data Sources

For brevity, requested acknowledgement wording is included only on the first mention of any source.

Base map: Esri, TomTom, Garmin, FAO, NOAA, USGS.

© OpenStreetMap contributors and the GIS user community.

North Sea & EEZ boundaries: VLIZ/marineregions.org, ICES

Bathymetry: EMODnet bathymetry consortium (2020). DOI:10.12770/bb6a87dd-e579-4036-abe1-e649cea9881a

Seabed substrates: EMODnet Geology project, <http://www.emodnet-geology.eu> (accessed on 1 January 2024), funded by the European Commission Directorate General for Maritime Affairs and Fisheries.

Wind speeds: Global Wind Atlas 3.0

“A free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: <https://globalwindatlas.info> (accessed on 1 January 2024).”

Waves: CEFAS Wavenet.

“Information provided by Cefas and funded by Environment Agency. Contains public sector information licensed under the Open Government Licence v3.0”

Fossil fuel infrastructure: OSPAR Inventory of Offshore Installations. <https://odims.ospar.org> (accessed on 1 January 2024)

Pipelines and cables: EMODnet Human Activities.

“Data/Information used in this report was made available by the EMODnet Human Activities project, www.emodnet-humanactivities.eu (accessed on 1 January

2024), funded by the European Commission Directorate General for Maritime Affairs and Fisheries.”

Shipping routes: IMO routes and VSS from Bundesamt für Seeschifffahrt und Hydrographie

“Datenlizenz Deutschland–Namensnennung–Version 2.0” (www.govdata.de/dl-de/by-2-0) (accessed on 1 January 2024)) genutzt werden. Datenlizenz Deutschland Namensnennung 2.0 <https://www.govdata.de/dl-de/by-2-0> (accessed on 1 January 2024) Quelle: Bundesamt für Seeschifffahrt und Hydrographie”

Danish sea lanes from Danish Government.

Customary shipping lanes from EMODnet Human Activities shipping density layer.

Nature designations: Natura 2000 areas: EU Environment Agency. © Directorate-General for Environment (DG ENV)

English MPAs: Natural England

Scottish MPAs: Marine Scotland

Norwegian environmentally designated areas: Norwegian Government

Military exercise areas: EMODnet Human Activities

Future offshore wind development areas: Belgium: Belgian government, marineatlas.be

Denmark: Danish Government (Søfartsstyrelsen)

England: The Crown Estate

Scotland: Marine Scotland

Netherlands: Rijkswaterstaat

Norway: Norwegian Water Resources and Energy Directorate

<https://veiledere.nve.no/havvind/identifisering-av-utredningsomrader-for-havvind/kart/interaktivt-kart/> (accessed on 1 January 2024)

Germany: Bundesamt für Seeschifffahrt und Hydrographie

“Nutzungsbestimmungen für die Bereitstellung von Geodaten des Bundes <http://www.gesetze-im-internet.de/geonutzv/GeoNutzV.pdf> (accessed on 1 January 2024)) genutzt werden. geonutz/20130319 Nutzungsbestimmungen für die Bereitstellung von Geodaten des Bundes <http://www.gesetze-im-internet.de/geonutzv/GeoNutzV.pdf> (accessed on 1 January 2024) Quelle: © BSH 2020”

Existing and planned offshore wind farms: As above, plus:

EMODnet Human Activities

OSPAR Renewable Energy Developments

Norwegian Government

Netherlands Enterprise Agency, <https://offshorewind.rvo.nl/page/view/367fe51f-cc7d-4bd1-81f0-4aad448078d8/general-information> (accessed on 1 January 2024)

Belgian government, <https://www.geo.be/home?l=en> (accessed on 1 January 2024)

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