Geospatial assessment of future floating offshore wind challenges: UK case study exploring drag anchor suitability and requirements

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ABSTRACT: The majority of the UK's future offshore wind (OW) will be located in deeper water (>60m) where the turbines will be on floating platforms, secured by mooring systems. The UK's government's net zero targets and energy security strategy require rapid deployment of new offshore wind capacity, at approximately ten times the rate of the past 5 years. This rapid growth, alongside the change to floating wind, presents many challenges, including the need for a new supply chain. This paper reports a geospatial analysis that explores the distribution of future offshore wind development around the UK sea regions and examines the implications for the mooring system market and supply chain. This analysis illustrates how geospatial analysis can be used to apply aspects of offshore wind design at a regional scale, providing associated market and supply chain forecasts, as well as the needs for research and the opportunities for innovation. This analysis focusses on the installation suitability and concept-level sizing of a common anchor type – the drag embedment anchor – across the UK sea regions. This methodology leads to an estimate of the number and weight of drag anchors and the length and weight of mooring chain needed for the offshore wind growth in each UK region for net zero. This analysis indicates the required major supply chain growth, which could present a bottleneck to meeting net zero.

1 **Introduction**

1.1 *Offshore renewable energy growth*

Three global drivers are pushing up the required rate of offshore renewable energy (ORE) installation: (i) increasing demand for energy due to a growing and increasingly wealthy population, (ii) decarbonisation of the economy to mitigate the climate emergency and (iii) increasing desire for local energy security to reduce the vulnerability to geopolitical events.

In the United Kingdom (UK), these drivers led to a commitment to carbon neutrality by 2050 (CCC, 2020) as well as an increased ramp-up of ORE capacity for energy security (HMG, 2022), resulting in a target of 50 GW of offshore wind (OW) capacity by 2030 (HMG, 2022). This 2030 target has grown from 30 GW in 2019 (HMG, 2019), then 40 GW in 2020 (HMG, 2020) (see Figure 1).

For OW capacity in the UK beyond 2030, three published Scenarios, A-C, are illustrated in Figure 1, based on the UK's Sixth Carbon budget (CCC, 2020) and the Offshore Renewable Energy Catapult forecast (ORE Catapult, 2020). The base case of Scenario A involves 65-140 GW of OW capacity by 2050, depending on societal and innovation effects (CCC, 2020). Scenario B adds the domestic hydrogen economy being fed by electrolysis from OW (110-226 GW) (CCC, 2020). Scenario C incorporates hydrogen export (350-466 GW) (ORE Catapult, 2020). These scenarios require OW installation at a rate of 5-15 GW/year, i.e., a 5-15 times increase relative to current installation rate.

1.2 *Finding space for the UK's offshore wind growth*

These targets form a basis for assessing the ocean space requirements for future OW, as well as supply chain needs. In this paper, we present a GIS-based analysis that examines (i) the likely regional distribution of future OW growth, (ii) the suitability of these new development regions for a common anchoring type – the drag embedment anchor – and (iii) the resulting needs for supply chain growth.

The starting point for this analysis is a study of the likely ocean space where future OW will be developed (Putuhena et al., 2023). The study reviewed 34 constraint layers due to anthropogenic, ecological, metocean and geomorphic features or uses of ocean space. The acceptable level of constraint overlap was calibrated based on existing OW leases, and the available ocean space was filtered, eliminating areas that had a higher level of constraint. The analysis focused on areas within the 90th percentile for water depth and distance from shore of the UK Exclusive Economic Zone (EEZ) clipped at 0-1000 m water depth, since these would be the most accessible and therefore attractive areas for development. The 90th percentile for water depth and distance from shore in UK waters correspond to 227 m and 197 km respectively. The mapping has been further refined for the present study to remove isolated regions of sea space that could not be aggregated into a wind farm. After this filtering, the remaining available area is shown in Figure 2[A], with the majority (94%) having water depth suited to floating wind (> 60 m), shown in the deeper blue.

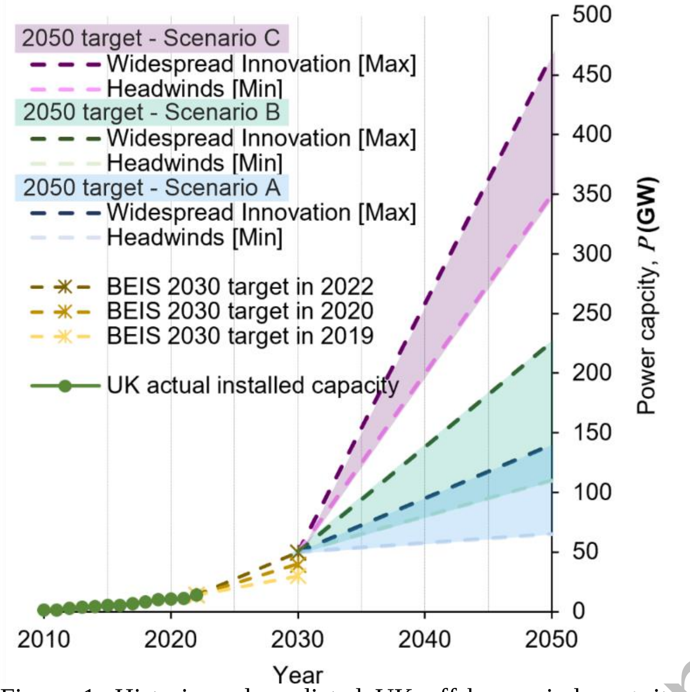


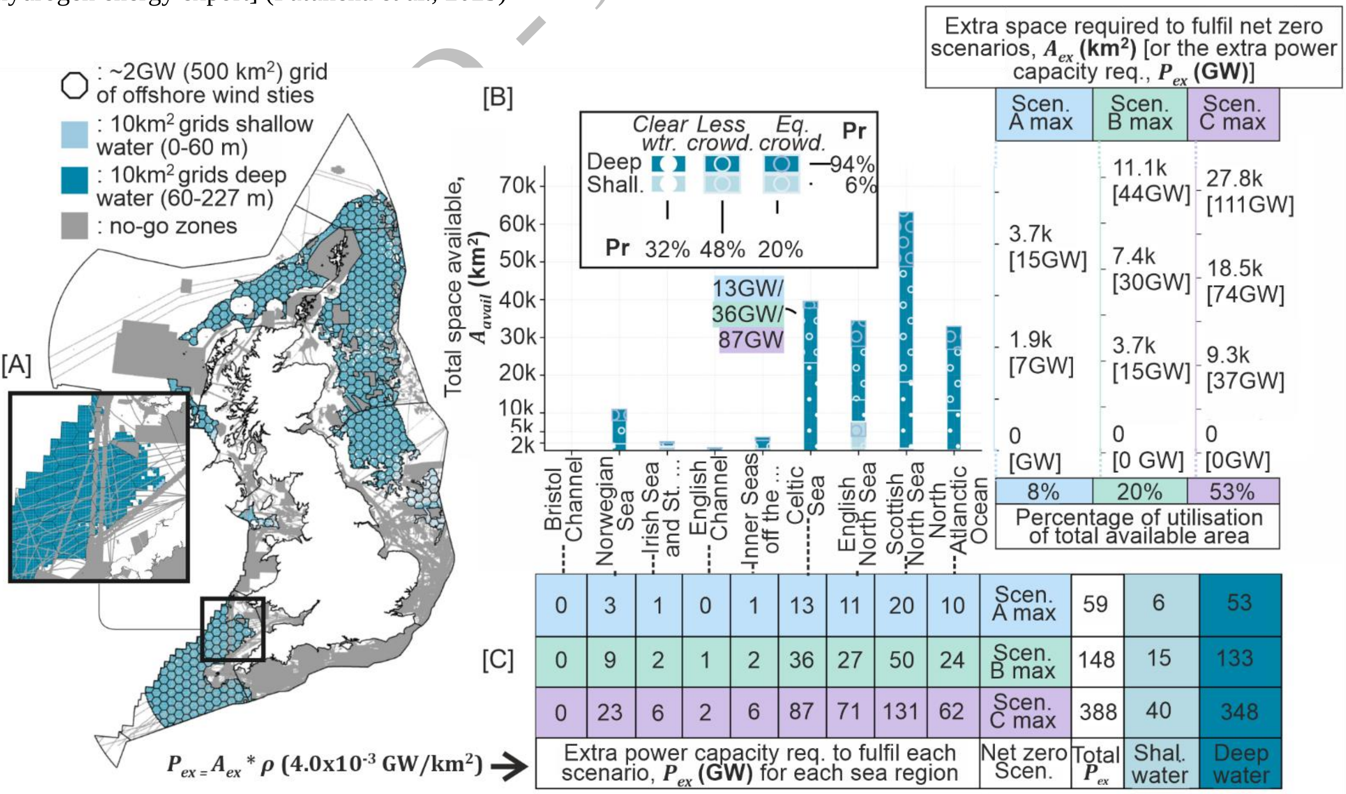
Figure 1. Historic and predicted UK offshore wind capacity (GW) to meet different net zero scenarios [Scenario A -domestic electricity, Scenario B – domestic green hydrogen, and Scenario C- hydrogen energy export] (Putuhena et al., 2023)

It is assumed that the future capacity is divided between the UK sea regions in proportion to their available space. The growth in OW represents a major expansion into the available ocean space: under the maximum capacity within Scenario C, 53% of the available space is utilised for OW. The sea regions that absorb the largest future growth are the Scottish North Sea and the Celtic Sea, taking 131 GW and 87 GW of OW, respectively. The detailed breakdown of ocean space and installed capacity in each sea region under each Scenario is set out in Figure 2[B-C]. These region-by-region estimates of future OW capacity provide a basis to assess the future technological, spatial planning and supply chain requirements needed to meet the overarching net zero goal. In this paper, we use anchoring for floating wind as a technological requirement example, and we focus on the applicability of drag embedment anchors and supply chain requirements.

2 Assessment for drag anchor suitability

2.1 *Suitability assessment method for drag anchors*

The suitability of the sea region in each gridsquare for drag anchor usage is assessed from the regional ground model data, presence of marine protected areas/fisheries grounds, and the anchor parameters of dry weight (W_{da}), penetration depth (z_{sb}), drag distance (x_{sb}) and ultimate holding capacity (F_{UHC}).



Bristol Channel	Norwegian Sea	Irish Sea and St. ...	English Channel	Inner Seas off the ...	Celtic Sea	English North Sea	Scottish North Sea	North Atlantic Ocean	Net zero Scen.	Total P_{ex}	Shal. water	Deep water
0	3	1	0	1	13	11	20	10	Scen. A max	59	6	53
0	9	2	1	2	36	27	50	24	Scen. B max	148	15	133
0	23	6	2	6	87	71	131	62	Scen. C max	388	40	348

Extra power capacity req. to fulfil each scenario, P_{ex} (GW) for each sea region

Figure 2. [A] Available space in UK waters for future OW (developing areas equally or less crowded than current sites), [B] Required area by sea region for Scenarios A-C, [C] Table showing [B] data in GW (all are modified from Putuhena et al., 2023, following the spatial filtering used in this paper)

The regional ground model uses the British Geological Society (BGS) dataset that describes the presence of rocky and non-rocky seabed and the Quaternary soils (by thickness range [0-5, 5-20, 20-30, 30-50, >50m] and lithological type [Soft/Firm to Hard Mud, Soft/Firm to Hard Layered soil/interbedded, Sand and Gravel, Diamict or undifferentiated]). The marine protected areas and fisheries grounds were obtained from Joint Nature Conservation Committee (JNCC) and Department for Environment, Food & Rural Affairs (Defra) respectively. The anchor performance uses standard charts for the Vryhof Stevpris Mk6 (Figure 3).

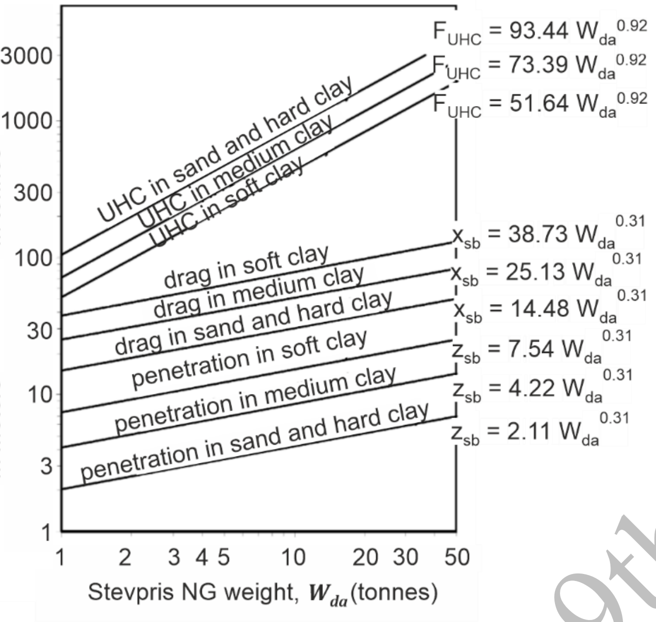


Figure 3. Fitted relationships for Stevpris Mk6 performance (modified from Randolph & Gourvenec, 2017; Vryhof, 2015) .

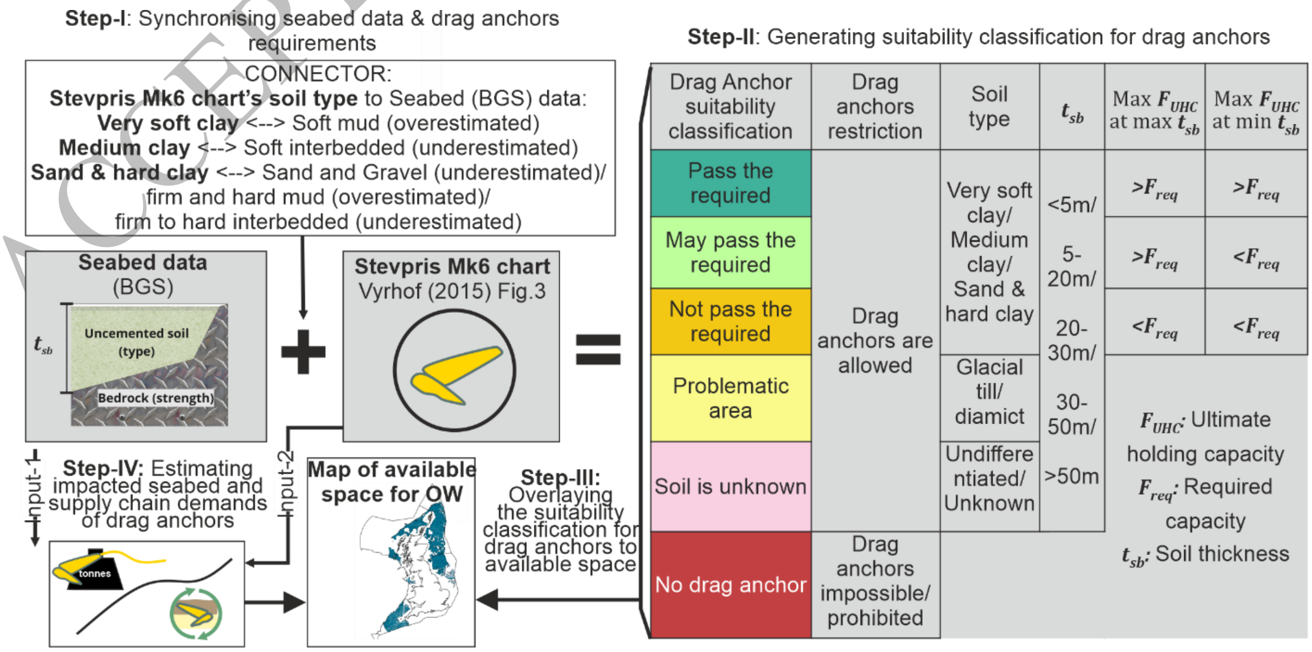
The assessment workflow of the dataset is depicted in Figure 4. First, the ground model is connected with the performance measures. In this case the Quaternary soil type defined by the BGS was simplified and mapped to each soil type defined in the Stevpris Mk6 chart (i.e., either soft clay, medium clay, or sand/hard clay) (see CONNECTOR box in Figure 4). This simplification may under- or over-estimate the shear strength of some lithologies given in the dataset, but for the purposes of a regional study is an acceptable approach.

Second, a traffic light system that distinguishes the suitability level for drag anchors from no installation (red), unknown (pink), problematic (yellow), not suitable (amber), may be suitable (light green), to suitable (green) is defined. This categorization is based on specifications of (a) drag anchor restrictions, (b) soil type, (c) soil thickness, and (d) required capacity (***F_{req}***) as described in the right-hand table in Figure 4. Drag anchors are impossible to be installed in rocky seabed environment and can be harmful to important ecological environments. We classify three different version (V) of restrictions on drag anchor use:

- V1– no drag anchor use on rocky seabed & marine protected areas & fishery grounds,
- V2– no drag anchor use on rocky seabed & marine protected areas, and
- V3– no drag anchor use on rocky seabed.

Drag anchor suitability is unknown in the undifferentiated Quaternary soil type; installation of drag anchors is problematic in glacial tills (Kay et al., 2021); and glacial till is represented in BGS seabed data as Diamict seabed in the Quaternary layer.

Drag anchors can be installed in other soil types, but the suitability depends on the penetration depth that can be achieved, which depends on the Quaternary thickness level. By using the Stevpris Mk6 chart relationship, for each gridsquare, ***F_{UHC}*** based on depth, ***z_{sb}*** and soil type is estimated. ***F_{UHC}*** is checked for the given Quaternary thickness range, whether that range is below (not pass), crossing (may pass), or above (suitable) the determined ***F_{req}***.



CONNECTOR:
Stevpris Mk6 chart's soil type to Seabed (BGS) data:
Very soft clay <--> Soft mud (overestimated)
Medium clay <--> Soft interbedded (underestimated)
Sand & hard clay <--> Sand and Gravel (underestimated)/ firm and hard mud (overestimated)/ firm to hard interbedded (underestimated)

Drag Anchor suitability classification	Drag anchors restriction	Soil type	t_{sb}	Max F_{UHC} at max t_{sb}	Max F_{UHC} at min t_{sb}
Pass the required	Drag anchors are allowed	Very soft clay/ Medium clay/ Sand & hard clay	<5m/ 5-20m/ 20-30m/ 30-50m/ >50m	$>F_{req}$	$>F_{req}$
May pass the required				$>F_{req}$	$<F_{req}$
Not pass the required				$<F_{req}$	$<F_{req}$
Problematic area		Glacial till/ diamict			
Soil is unknown		Undifferentiated/ Unknown			
No drag anchor	Drag anchors impossible/ prohibited				

F_{UHC}: Ultimate holding capacity
F_{req}: Required capacity
t_{sb}: Soil thickness

Figure 4. Workflow to define drag anchor zonation in the UK waters using the base map of available space, seabed dataset.

The required capacity F_{req} depends on the turbine size and mooring system, which cannot be determined in the scope of this work. Instead, a simplification of three different values of required capacity of 10 MN (low estimation), 20 MN (mid), and 30 (high) MN is adopted. The drag anchor sitability mask is applied to the available space in deep (60-227m) waters of the UK-EEZ.

2.2 *Suitability results for drag anchor usage*

Figure 5 shows the results of the traffic light system mapping for a selected case of: 20 MN required capacity and V2 restriction, i.e. no drag anchors on rocky seabed & marine protected areas. This mapping focuses on the primary future wind development areas: Celtic Sea, North Atlantic Ocean, Scottish North Sea and English North Sea. The Scottish North Sea has the greatest proportion of area suitable for drag anchors at ~70%. The English North Sea is approximately equally divided by areas that are suitable, problematic, unknown, and impossible/ prohibited (20-25% each). In the Celtic Sea, the majority of the area is unknown (~60%) due to uncertainty regarding the sediment thickness. However, a significant proportion is unsuitable due to only a thin sediment layer or exposed rock. In the North Atlantic Ocean, ~40% is problematic and <20% is suitable for drag anchor installation.

3 **Supply chain volume for drag anchor usage**

3.1 *Definitions of supply chain needs*

The supply chain volume requirements measured here are the total weight of drag anchors (W_{da}) and chain weight (W_{ch}) for those anchors. These are estimated based on the UK capacity targets for offshore wind, applied across the gridsquares suited to drag anchors. To determine weight, W_{da}, penetration depth, z_{sb}, and drag distance, x_{sb} for each drag anchor for different soil types in each gridsquare, the anchor weight, W_{da} and ultimate holding capacity, F_{UHC} relationship for the Stevpris Mk6 in Figure 3 is used, taking F_{req} =20MN.

3.2 *Method to measure supply chain requirements*

To determine the supply chain requirements, the weight of drag anchor needed, W_{da}, is determined from the W_{da}~F_{UHC} relationship for the Stevpris Mk6 (Figure 3), by assuming F_{req}=20 MN as the targeted F_{UHC}. To estimate the required chain weight W_{ch}, chain length was determined from trendlines drawn through published data of fairlead anchor distance (r) and water depth (z_w) ratio for each z_w (Line(i-iii) in Figure 6) and unstretched chain length (L_{ch}) and r ratio for each z_w (Line(iv) in Figure 6. Line(i) is the trendline from r/z_w data in Ma et al. (2019), Line (ii) is the trendline from r/z_w data in Allen et al., 2020; Connolly & Hall, 2019; Ma et al., 2019; Pillai et al., 2022, and Line (iii) is the trendline from $r/z_w<4$ data in Ma et al., 2019 plus Pillai et al. (2022) baseline data. Line(iv) is the trendline from all L_{ch}/r data in Connolly & Hall, 2019.

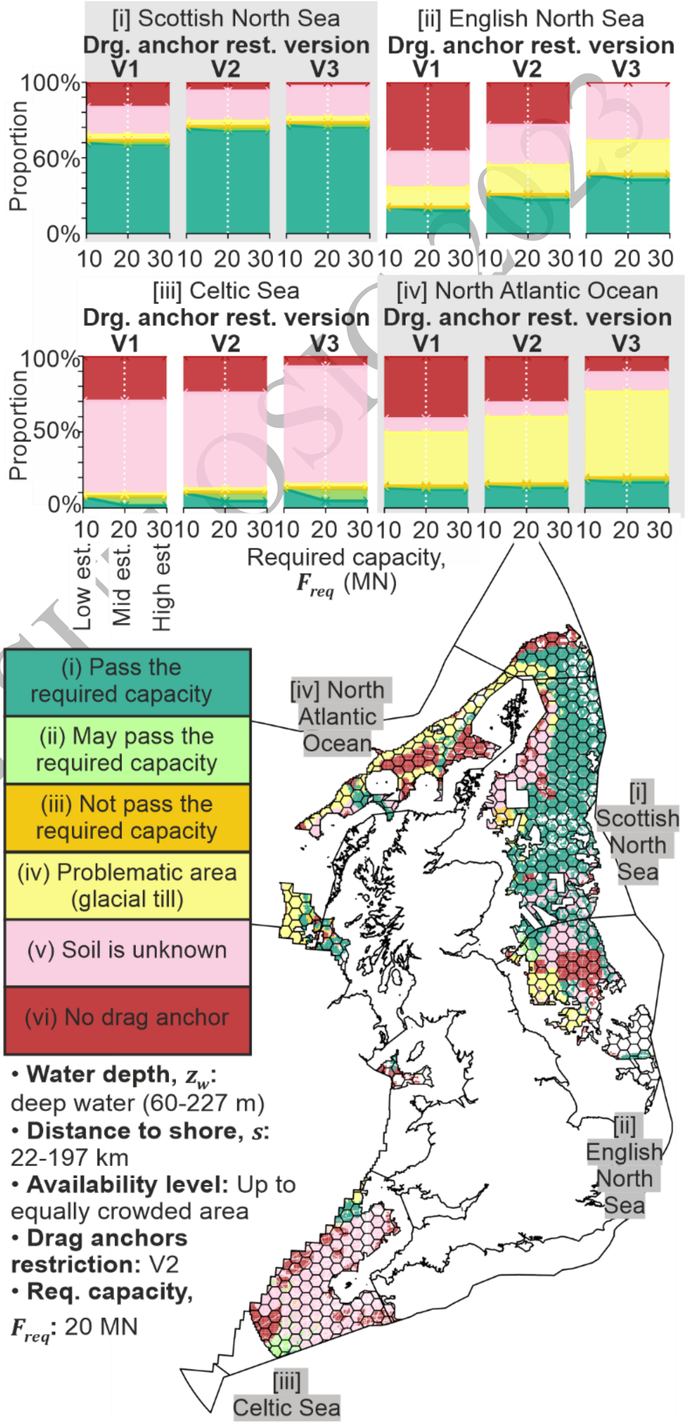


Figure 5. Spatial map of drag anchor suitability for a given case as stated in the figure, for definitions of V1-3 of drag anchor restriction see text.

By using Line (iii), considered as the most realistic line that could represent an up-to-date turbine development r/z_w ratio (Pillai et al., 2022), and Line (iv), the chain length (L_{ch}) was determined for each anchor and converted to weight through the W_{ch}/L_{ch}

parameter of R5 studless given for a proof load equal to F_{req} in Vryhof (2015) . Line (iii) shows that r is ~4.5, 4.0, 3.0, and 2.0 times of z_w at z_w of 50, 100, 200, and 1000 m respectively. This gives (in units of *[m]*):

$$L_{ch} = (0.005 z_w^{1.77} + 10.15 z_w^{0.77}) \qquad \textbf{(eq.1)}$$

The weight of R5 studless chain (using units of *[tonnes]*) is defined as:

$$W_{ch} = \left(0.38 F_{req}^{2} + 22 F_{req} - 1.26\right) * 0.001 L_{ch} \qquad \textbf{(eq.2)}$$

with z_w in units of [m] and F_{req} in units of [MN].

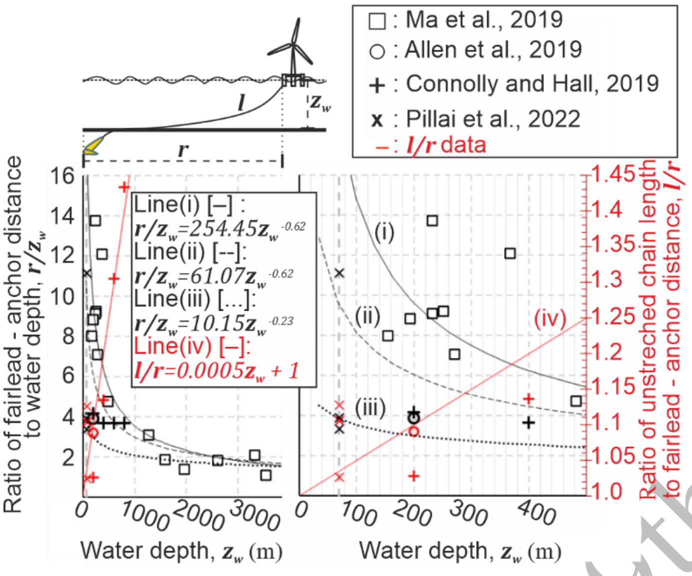


Figure 6. Estimation of fairlead-anchor distance (**r**)/ water depth (**z_w**) and chain length (**L_{ch}**)/ **r** across water depths (**z_w**) based on the analysis of published data (right graph is zoom-in of left chart for low water depths.

3.3 *Results of required supply chain volume*

In each gridsquare, the required weight of anchor, W_{da}, and chains, W_{ch} per km^2 were calculated with the assumption of 3 anchors per floating OW turbine and a development density of 1 turbine per 4 km^2. These values, factored by 500, indicate the results for a single wind farm of 2 GW size using 16 MW turbines. Other assumptions can be applied, leading to a simple scaling of the results.

Figure 7 maps the weight of the anchor W_{da} required across the suitable area for drag anchors in a case of F_{req} = 20 MN and the restriction level V2–'no drag anchors on rocky seabed & marine protected areas'. There are two distinct values as a function of the soil type. The gridsquares in dark purple are soft clay soil, associated with higher W_{da} (20k tonnes) than gridsquares in light purple representing sand/hard clay soil (11k tonnes). This is due to the effect of different soil types on the capacity given by the Stevpris Mk6. For soft clay, the same anchor weight results in deeper penetration depth and a lengthier drag, but lower F_{UHC} than sand/hard clay.

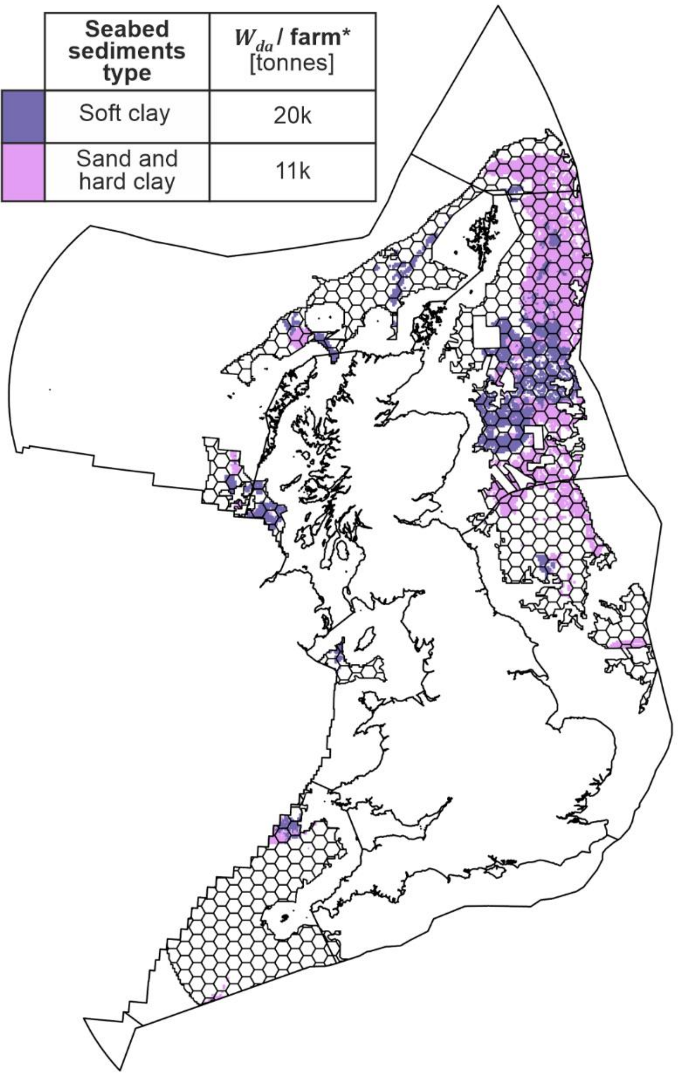


Figure 7. Spatial map of different seabed sediment type across the UK waters and drag anchor weight needed, W_{da} per farm for different seabed sediment type in areas suitable for drag anchor (green area defined in Figure 5). *(/farm) means for one farm of 2 GW OW (500km^2).

Figure 8 shows the weight of chain W_{ch}, which is a function of z_w, with 3 different bands of colors reflecting different water depth ranges. The map shows the locations where water depths are between 60-100 m that requires 92-138 km length and 55-82k tonnes weight of chain per 2 GW OW farm. Those numbers increase for water depth range 100-150m (length: 138-194 km & weight: 82-115k tonnes) and 150-227 m (length: 194-277 km & weight: 115-164k tonnes).

Table 1 shows the list of key parameters including the area available (ΣA_{avail}) and suitable for drag anchors ($\Sigma A_{avail,da}$) in each sea region across the whole UK waters as well as the average needed for one 2 GW OW farm site of 500 km^2 area ($\overline{W}_{farm,da}$, $\overline{W}_{farm,ch}$). These results are then aggregated into the total of anchor and chain weights, ($W_{region,da}$, $W_{region,ch}$) for different sea region and the whole UK waters. Average and total weights for drag anchors and chain within a farm and a region are calculated as below in units of *[tonnes]*, ***A*** in *[km^2]*, ***n*** is total gridsquares that are suitable for drag anchors, ***m*** is the total of gridsquares that are suitable for drag anchor in each region, and $A_{2GW,OW}$ = 500 km^2. The gridsquares are the underlying 10 km^2 cells over which the quantities are gridded.

$$\overline{W}_{farm,da/ch} = \sum_{i=1}^{n} W_{da/ch}(i)/A(i) * A_{2GW,OW} \quad \textbf{(eq.3)}$$

$$W_{region,da} = \sum_{i=1}^{m} W_{da}(i) \quad \textbf{(eq.4)}$$

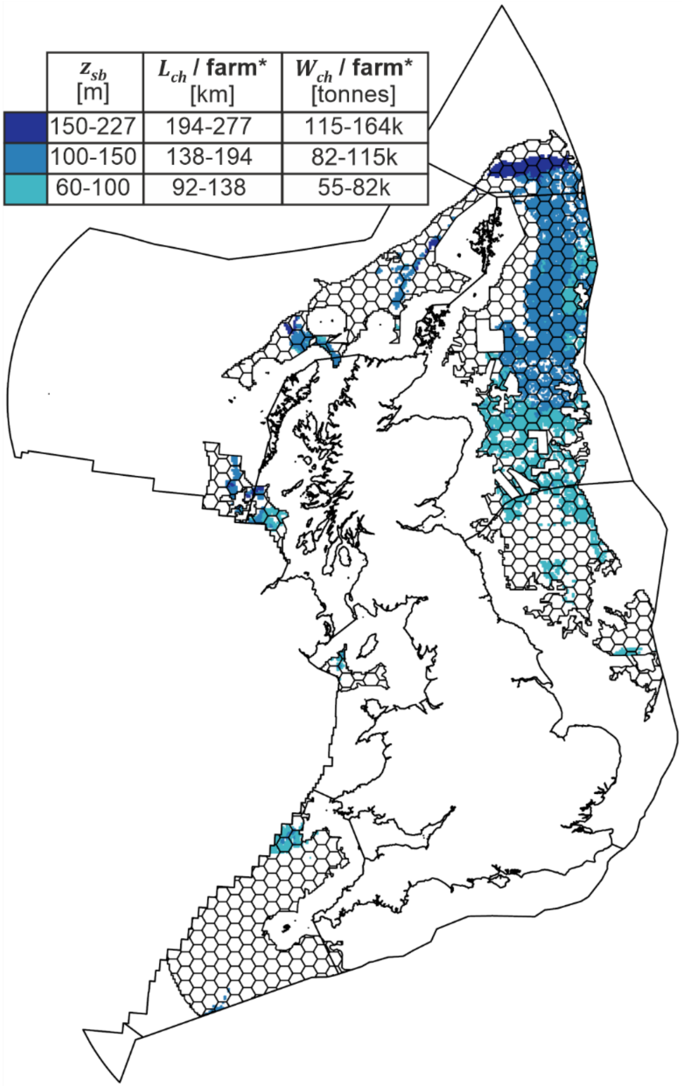


Figure 8. Spatial map of different water depths, z_w and chain weight needed, W_{ch} per farm in areas suitable for drag anchors (green area defined in Figure 5). *(/farm) means per farm of 2 GW OW (500km^2).

From the total value of area available that pass the required capacity of 20 MN and V2– no drag anchor use on rocky seabed & marine protected areas, for the whole UK, Table 1 indicates how much weight of drag anchors/chains will be needed to use those whole area suitable for drag anchor in the UK waters as OW sites. Combining those values with the targets for net zero by 2050 (Figure 1) and using 4.0 MW/km^2 of energy density, predictions of impacted seabed and supply chain needed for different targets of GW capacity of OW that would be acquired can be made, as shown in Figure 9.

4 Discussion: Future OW challenges

The spatial analysis conducted in this paper uses drag anchors as an example technology solution for floating OW, since floating OW is a key solution to optimise the available space for OW, given that it mostly lies in deep water, > 60 m. The analysis develops a simple analytical method to provide estimates of drag anchor suitability and size, as well as supply chain requirements (anchor and chain) across the available space for new OW farms in the UK waters. Based on the results of the analysis, two major challenges to the growth of floating OW to meet the net zero targets by 2050 become apparent.

The first challenge is the different levels of suitability of different sea regions, which will constrain the distribution of future OW across the available space in each sea region. In the top four regions with available space for future OW (Figure 2), only the Scottish North Sea has a significant proportion of area (~70%) that is suitable for drag anchors from the total available areas. In the Celtic Sea, where 4 GW of future floating OW has been planned by 2030, no more than 5% is defined suitable for drag anchors, while ~70% of the area is unknown due to undifferentiated soil type data that is mostly comprised of a thin (<5 m) layer of Quaternary soil. Meanwhile, in the English North Sea and North Atlantic Ocean, a high proportion of area is problematic for drag anchors, where glacial till is found. In these cases, anchoring technologies other than drag anchors will need to be adopted, or detailed investigations will be needed to prove or extend the capability of drag anchors.

The second challenge applies generally across all regions. The spatial analysis of suitable area for drag anchors serves as a reference model to assess supply chain volume requirements. For example, to achieve the maximum target with domestic electrification, Scenario-A is to install up to 9k turbines (@16 MW) (Figure 9) in UK waters. If these turbines use the mooring system approach analysed here, then ~7.4Mtonnes of steel are required for drag anchors and chain (~1.0M tonnes for drag anchors and ~6.4M tonnes for chain) between now and 2050 (Figure 9). This is equal to ~250,000 tonnes per year or ~900 tonnes per turbine or ~60 tonnes per MW.

As a comparison, the rate of steel needed for the drag anchors and chains per turbine and per MW for are respectively 60% and 30% of the total steel used for fixed-bottom foundations currently installed in Scotland (i.e., Robin Rigg, Seagreen, Neart na Gaoithe, Beatrice, Moray East, and Aberdeen sites, which used ~1500 tonnes per turbine or ~187 tonnes per MW) (ORE Catapult, 2022). In addition, the

Table 1. Key assessments for each sea region.

	Bristol Chnl.	Norwegian Sea	Irish Sea and …	English Chnl.	Inner Seas …	Celtic Sea	English North Sea	Scottish North Sea	North Atlantic Ocean	Total
Space suitable for new 2GW farms, ΣA_{avail} x10^3 [km^2]	-	11.0	2.3	0.7	3.5	39.5	34.0	63.0	33.0	187.0
Drag anchor suitable areas*, $\Sigma A_{avail,da}$ x10^3 [km^2]	-	5.8	0.3	-	2.1	1.7	5.9	42.5	4.3	62.6
Average drag anchor weight needed per 2GW farm, $\overline{W}_{farm,da}$ [tonnes]	-	1.1E+4	2.0E+4	-	2.0E+4	1.6E+4	1.1E+4	1.4E+4	1.7E+4	-
Total drag anchor weight needed, $W_{region,da}$ [tonnes]	-	1.3E+5	1.3E+4	-	8.0E+4	5.3E+4	1.4E+5	1.2E+6	1.5E+5	1.8E+6
Average chain weight needed per 2 GW farm, $\overline{W}_{farm,ch}$ [tonnes]	-	1.3E+5	7.9E+4	-	8.8E+4	8.6E+4	6.6E+4	9.3E+4	1.1E+5	-
Total chain weight needed, $W_{region,ch}$ [tonnes]	-	1.5E+6	5.2E+4	-	3.5E+5	2.9E+5	7.8E+5	7.9E+6	9.4E+5	1.2E+7

floating turbines also require a substructure fabricated from steel. The limited data from Scottish deployments to date indicate an average substructure mass of ~290 tonnes per MW (ORE Catapult 2022). Overall, therefore, this analysis indicates a steel volume requirement for future floating wind that is two times higher per MW of capacity.

The more challenging aspect for this material requirement is the rate of production. The acceleration of offshore wind deployment (Figure 1) means a 5-15 times higher capacity installation rate. For example, the steel requirement for drag anchors and chain of ~250,000 tonnes per year to meet the top of Scenario A is five times higher than the recent rate of steel usage for fixed foundations in Scotland (~54,000 tonnes per year, ORE Catapult, 2022). For the higher net zero targets, a higher supply chain production rate is needed, and the supply chain is meanwhile also required to produce the floating substructures.

5 Summary

In this paper, a spatial analysis of suitability of drag anchors as a technological solution for floating OW is assessed across the UK waters. The spatial analysis allows the regional distribution of future OW growth to be assessed, and then linked to the suitability of these new development regions for a common anchoring type – the drag embedment anchor – and the implications for supply chain requirements. The results lead to a discussion of two major future challenges: (i) how to optimise the distribution of future offshore wind, reflecting the technological constraints associated with aspects such as anchoring, and (ii) the increasing volumes of mooring elements – chains and anchors – that are required to meet the net zero targets, and the resulting supply chain growth.

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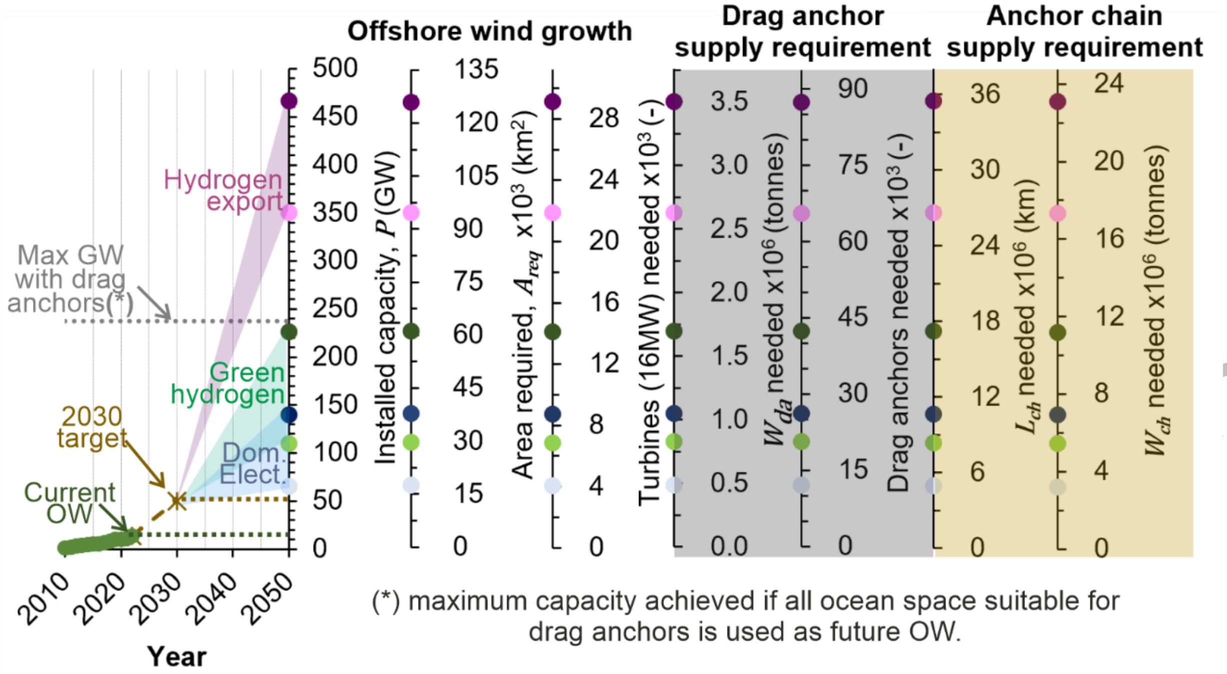

Figure 9. Projected supply chain requirements from drag anchor deployment in suitable UK sea regions.

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