ARUP

The Crown Estate

Celtic Sea Engineering Risk Assessment

Engineering Risk Assessment

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Notice

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1. Executive summary

Context of the spatial refinement process

The Crown Estate (TCE) has undertaken spatial refinement of floating offshore wind (FLOW) projects in the Celtic Sea. The output of this spatial refinement process was the selection of the Project Development Areas (PDAs) that are being offered to potential bidders through Leasing Round 5.

The spatial refinement process that TCE conducted is described in the Celtic Sea Floating Offshore Wind Leasing Round 5: Site Selection Methodology report. As described in that report TCE completed spatial refinement as follows:

- Initial broad Areas of Search (AoS) were identified through extensive engagement with a variety of market, marine and statutory stakeholders.
- Further engagement and analysis supported distilling these AoS down to five Refined Areas of Search (RAoS, A-E).
- The RAoS have been further refined into three 1.5GW PDAs that are being offered to potential bidders through Leasing Round 5.

Scope and purpose of the Arup engineering risk assessment

Arup undertook a high-level engineering risk assessment which was an input to TCE's spatial refinement process. That scope of work, summarised in this report, aimed to provide TCE with an improved understanding of the technical viability and commercial attractiveness of the RAoS and PDAs to inform the wider spatial refinement process and decision making.

The Engineering Risk Assessment included for the RAoS:

- A high-level desk-based review of the physical environmental conditions,
- An assessment of the potential and key engineering risks to FLOW development, and
- A high-level and relative assessment of levelised cost of energy (LCOE).

Engineering risk assessment approach

The engineering risk assessment was a high-level qualitative risk assessment. A longlist of engineering risks was identified through a high-level review of the RAoS site characteristics. A shortlist of key engineering risks was defined based on those risks that were site specific across the RAoS and where sufficient information was available. The shortlisted key engineering risks were:

A. Seabed depth.

B. Depth to bedrock.

C. Bedrock lithology, specifically strength of bedrock for anchor installation.

D. Wave loading for installation (average wave height).

E. Wave loading for O&M (average wave height).

F. Metocean conditions for structural feasibility (extreme wave and wind conditions).

G. Shallow gas.

For each engineering risk, a qualitative assessment of the overall risk level for each RAoS was undertaken. This was performed by assigning Red, Amber, Green risk ratings based on the following definitions:

- RED: a level of technical risk which will **likely** be complex and / or costly to mitigate.

- AMBER: a level of technical risk which **may** be complex and / or costly to mitigate.
- GREEN: a level of technical risk which is **unlikely** to be complex and / or costly to mitigate.

RAoS engineering risk assessment results

Phase 1 of this assessment focused on the five RAoS. The high-level risk review indicated that four of the five RAoS (A, B, C and D) were deemed to be in the medium risk category, AMBER, considering the average maximum risk rating. This is based on picking the highest risk rating across all the key engineering risk categories for each hex-cell (see Figure 1), and then averaging this risk rating for each RAoS. The risk criteria which governed this conclusion were *seabed depth*, *wave loading for installation*, *wave loading for O&M* and *metocean conditions for structural stability*, all of which were rated as AMBER across all four of these RAoS.

The remaining RAoS (E) was deemed to be in the highest risk category, RED, considering the average maximum risk across all the key engineering risk categories. The risk criteria which governed this conclusion were *depth to bedrock*, *wave loading for installation* and *wave loading for O&M* which were rated RED for RAoS E.

LCOE assessment

LCOE was calculated using SCALE, Arup's proprietary offshore wind deployment and LCOE digital model. The LCOE results provided a more granular review of the feasibility of floating offshore wind within the RAoS, while quantitatively taking into consideration the relative contribution of the various components of the floating technology (support structure, mooring and anchors) to the overall LCOE. The output is suitable for relative assessment of LCOE across different geospatial locations within the model boundary, the results have been presented as normalised LCOE figures in this report. The results are subject to inherent uncertainty due to limitations in the data inputs and future uncertainty on a range of market and technology factors.

The results from the SCALE model indicated that the RAoS with the lowest LCOE were areas A and B, followed by C and D, with E having the highest LCOE. This corresponded to a general correlation of increasing LCOE with increasing water depth, wave height, and metocean conditions, which become more onerous moving towards the southwest within the Celtic Sea region.

Based on the analysis conducted within SCALE, all of the FLOW technologies considered within the assessment (steel semi-submersible, steel TLP and concrete barge) were found to be feasible across all RAoS. The lowest cost floating technology type selected across the whole SCALE model was the steel TLP with either driven or drilled piled anchors, depending on the depth to bedrock. This was as a result of the lower CAPEX cost associated with the support structure, when compared with the alternative technologies. Note that this assessment of the lowest cost floating technology type was based on a number of assumptions regarding the development and commercialisation of TLPs that were applied within the SCALE model and is inherently uncertain as market, technology and site specific factors are likely to impact on the optimal technology selection.

PDA assessment

Through TCE's broader spatial refinement process (not included within this scope or report), three PDAs of 1.5GW capacity were identified. Phase 2 of this assessment provided a summary of the risk assessment for each of the three PDAs (see Section 7).

- PDA 1 was rated as AMBER for the average maximum risk rating across all the key engineering risk categories. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock* and *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

- PDA 2 was rated as AMBER for the average maximum risk rating across all the key engineering risk categories. An area of RED risk was identified towards the north of the PDA, driven by *combined* *anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

- PDA 3 was rated as AMBER for the average maximum risk rating across all the key engineering risk categories. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock* and *strength of bedrock for anchor installation* as well as the *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

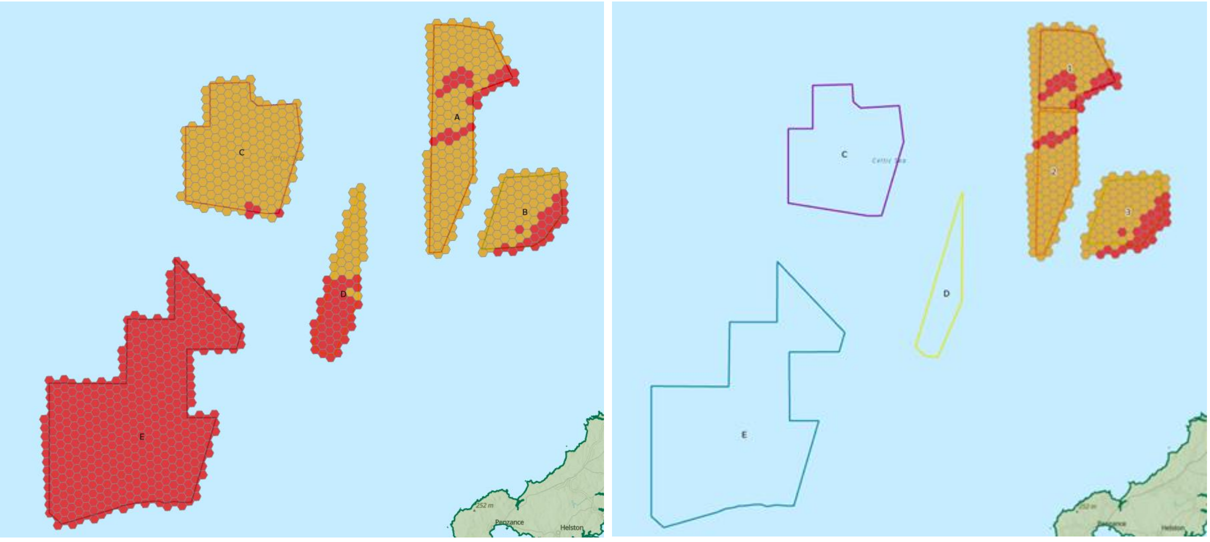


Figure 1 Maximum risk rating across RAoS, A to E (left) and PDAs, 1 to 3 (right)

Next Steps

It is expected that potential bidders will carry out an independent review of the PDAs as part of submitting a Leasing Round 5 bid. The assumptions and limitations set out in this report should be further assessed and considered through the development and design of a Round 5 project through site specific survey and assessment.

2. Introduction

2.1 Background to the Celtic Sea leasing round spatial refinement process

The Crown Estate is delivering Floating Offshore Wind in the Celtic Sea Leasing Round 5. Leasing Round 5 seeks to establish a new floating wind sector in the Celtic Sea off the coasts of South Wales and South West England. It is expected to be the first phase of commercial development in the Celtic Sea. The Crown Estate has developed an opportunity for the delivery of floating offshore wind projects in the Celtic Sea including three project development areas (PDAs) of roughly equal size, each with a potential capacity of up to 1.5GW, with the ability for developers to deliver the PDAs in up to three projects or phases of at least 300MW.

A description of the spatial refinement process that TCE conducted to inform the sites offered to bidders through Leasing Round 5 is in the Celtic Sea Floating Offshore Wind Leasing Round 5: Site Selection Methodology report. The process is summarised as follows:

- Initial broad Areas of Search (AoS) in the Celtic Sea were identified by TCE through extensive engagement with a variety of industry, market, marine, statutory and other stakeholders.
- Further engagement and technical analysis supported distilling these AoS down to five Refined Areas of Search (RAoS A-E).
- The RAoS have been further refined into three Project Development Areas (PDAs) by TCE which will be offered to bidders.

Arup was commissioned to support this process, providing an Engineering Risk Assessment of the RAoS (Phase 1) and PDAs (Phase 2). This assessment was used to inform the spatial refinement process in conjunction with various other refinement exercises and assessments undertaken by TCE and others. This wider work included stakeholder engagement with fishing communities, environmental groups, and other stakeholders, a Habitats Regulation Assessment, environmental surveys, and technical analysis among others.

2.1.1 Refined Areas of Search

The RAoS analysed in Phase 1 of this assessment are presented in Figure 2. The decision on the RAoS locations was made by TCE reviewing feedback received from stakeholders and completing targeted bilateral engagement following the determination of the initial broad Areas of Search.

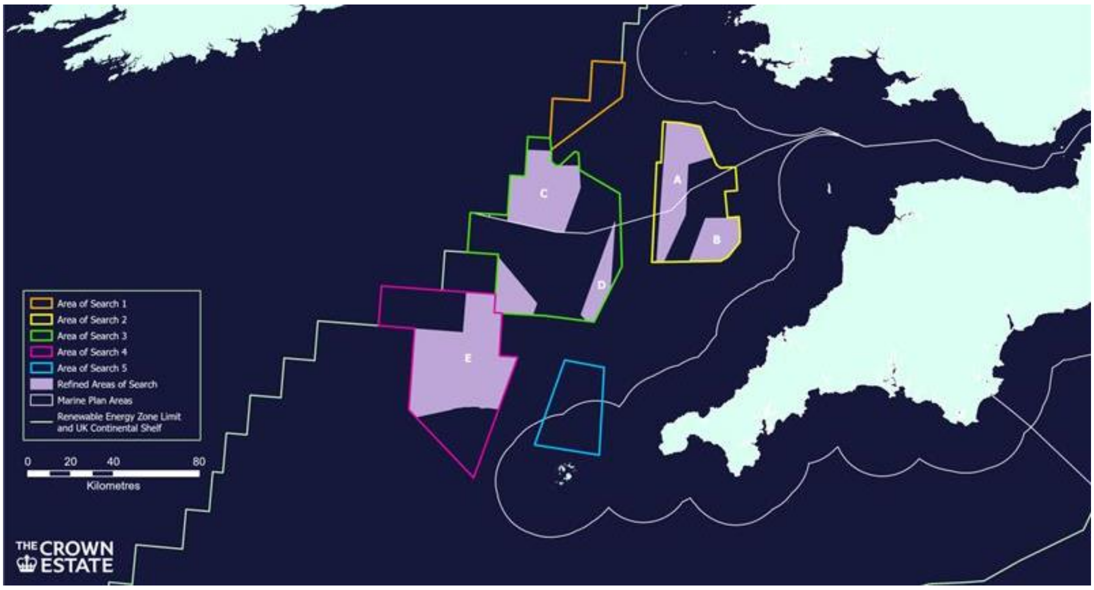


Figure 2 RAoS as at 14/09/2022 (TCE)

2.1.2 Project Development Areas

The PDAs reviewed in Phase 2 of this assessment are presented in Figure 3. The decision on PDA locations was determined by TCE taking into account output from Phase 1 of this assessment alongside other supporting work that informed TCE's spatial optimisation process.

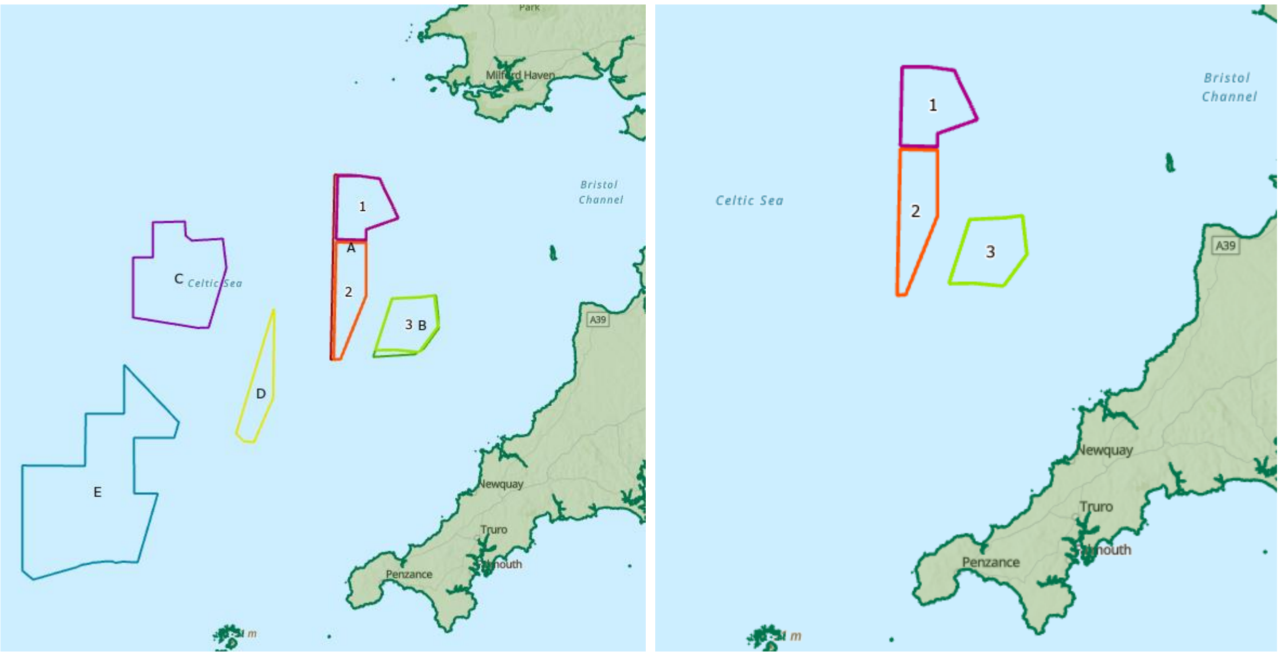


Figure 3 PDA areas 1-3 (shown within the RAoS on left)

2.2 Scope of work

The scope of work, summarised in this report, aimed to provide TCE with an improved understanding of the technical and commercial viability of the RAoS and subsequent PDAs to inform the spatial optimisation process.

This was achieved through a technical engineering risk assessment which included physical environmental risks, potential implications of those risks and their potential impact on relative levelised cost of energy (LCOE).

The scope covers a multi-stage process, developed in conjunction with TCE to focus on key risk areas, building in greater refinement across subsequent stages. The detailed methodology is described in Section 3, but at a high-level it includes:

- Preliminary site assessment across the RAoS to determine key engineering risks including:
  - Technical definition of key engineering risk parameters to determine the key areas of risk that merit further investigation,
  - Definition of the key technical site characteristics and associated engineering risks for the RAoS, and
  - Preliminary Red, Amber, Green (RAG) assessment of the identified risks for each RAoS summarised from an initial desk study review of relevant geospatial data.
- Review of FLOW technologies including:
  - High-level review of FLOW technology types including substructure and anchor / mooring configurations,
  - Shortlisting of FLOW technology combinations most likely applicable for deployment on Round 5 developments, and
  - A summary of their relevant technical limitations in the context of application of these FLOW technologies within the Celtic Sea.
- Follow up site assessment including:
  - Geospatial review of the key datasets against a granular 2.5km-diameter hexagonal grid across the RAoS to inform an updated RAG assessment of the shortlisted risks (a detailed list of all datasets utilised is provided in Section 3.5),
  - Aggregated review of all the risks across each of the RAoS assessing any potential risk combinations and the overall risk,
  - LCOE assessment using Arup's SCALE offshore wind deployment model, considering:
    - Relative LCOE across the RAoS.
    - FLOW technology type potential viability across the RAoS, likely preferred FLOW technology (considering lowest LCOE), and total number of FLOW technology solutions considered likely viable per 2.5km-diameter hexagonal grid cell.
  - PDA site assessment using the same methodology as described above including review of PDAs and update of RAG risk assessment specifically for the PDAs.

2.3 Structure of report

The report is structured into the following sections:

- **Section 3 Methodology** provides a summary of the approach taken in carrying out this technical engineering risk assessment covering both Phase 1 (RAoS) and Phase 2 (PDAs).
- **Section 4 FLOW technologies** summarises the shortlisted five FLOW technology combinations that are considered in the engineering risk assessment and SCALE modelling.
- **Section 5 Engineering risk assessment** summarises the results of the technical site assessment including the following sections:
  - **Section 5.1 and 5.2** summarise the key engineering risks providing an overview of the longlist of considered engineering risk parameters, risks that were considered but were not included within the RAG assessment, and the shortlisted risks carried forward into the RAG assessment,
  - **Sections 5.3 RAG assessment of the key engineering risks** provides a summary of the desk-study assessment for each of the shortlisted risks across each of the RAoS, and
  - **Sections 5.4 to 5.6** provide further analysis and summary of the RAG assessment, considering combined and maximum risks across each of the RAoS.
- **Section 6 LCOE modelling** describes the methodology and limitations of Arup's SCALE model and describes the relative LCOE output and detailed FLOW technology analysis completed within the model.
- **Section 7 PDA assessments** describes the RAG assessment for each of the PDAs.
- **Section 8 Conclusions** describes the overall conclusions including the results of the analysis across the RAoS and the PDAs.

2.4 Definitions

The report uses these terms:

Term	Acronym	Definition
Area of Search	AoS	Large areas of sea space identified in the Celtic Sea region following detailed spatial modelling and stakeholder engagement, within which smaller Project Development Areas will be located.
Annual Energy Production	AEP	Total energy generated from a generation asset (e.g. an offshore wind farm) over an annual period in megawatt-hours (MWh).
British Geological Survey	BGS	A research organisation providing geoscientific data, information and knowledge.
Capital Expenditure	CAPEX	Spend to construct a project.
Decommissioning Expenditure	DECEX	Spend to decommission a project at end of life.
Development Expenditure	DEVEX	Spend to develop a project up to the point of construction.
Drive, Drill, Drive	DDD	Technique for installing piles combining drilling and driving, utilised when driving alone may encounter significant resistance or difficulty during the installation process.
European Marine Observation and Data Network	EMODnet	A network of organisations that work together to collect, process and make available marine data.
Floating Offshore Wind	FLOW	Wind turbines on floating offshore substructures.
Geographical Information System	GIS	A system for analysing and mapping data related to positions on the Earth's surface.
Habitats Regulations Assessment	HRA	A process that determines a proposed plan or project's impact on a protected European site.
H_s - Significant wave height	H_s	A common measure of the height of ocean waves, it is the equivalent of the average height of the highest one third of waves over a defined period (e.g. hourly).
H_{s_50yr} - 50-year extreme significant wave height	H_{s_50yr}	The significant wave height (H_s) expected to be exceeded only once in a 50-year period. NB. For the purposes of this study we have assumed that H_{m0} (corresponding to input data available) approximates to H_s.
IEC 61400	-	An international standard published by the International Electrotechnical Commission (IEC) containing a set of design requirements for wind turbines. IEC 61400 contains design classes for wind turbines covering specific wind conditions [21].

Term	Acronym	Definition
Key Engineering Risks	-	The most likely significant site specific physical environmental risks (and implications of these risks through to LCOE) that vary across the RAoS and enabled a relative risk assessment across the RAoS for the purposes of this study.
Levelised Cost of Energy	LCOE	Levelised Cost of Energy (often, Levelised Cost of Electricity) is the lifetime costs of building and operating a generation asset, expressed as a cost per unit of energy produced. It is an industry standard metric and includes the cost of all components across the lifecycle of a wind farm, including development (DEVEX), capital (CAPEX), operational (OPEX) and decommissioning (DECEX).
Operation and Maintenance	O&M	Activities during the operational life of a project to ensure the safe and economic running of the project.
Operational Expenditure	OPEX	Spend to operate a project.
Project Development Areas	PDAs	The final areas of sea space identified through targeted bilateral engagement with market and marine stakeholders, within which one or more individual floating offshore wind project could be developed.
Quaternary deposit	-	The most recently deposited geologic strata found at or near the earth's surface in valleys, plains, seashores and on the seabed.
Red, Amber, Green Assessment	RAG	A high-level risk assessment that categorises risks based on defined qualitative thresholds.
Refined Area of Search	RAoS	Smaller areas of sea space identified through further stakeholder engagement (subsequent to AoS), environmental and technical analysis.
SCALE	-	Arup's digital offshore wind LCOE tool.
Tension Leg Platform	TLP	A type of floating offshore wind support structure.
The Crown Estate	TCE	A significant national landowner with a diverse £16 billion portfolio that includes urban centres and development opportunities; one of the largest rural holdings in the country; Regent Street and St James's in London's West End; and Windsor Great Park. TCE also manage the seabed and much of the coastline around England, Wales and Northern Ireland, playing a major role in the UK's world-leading offshore wind sector.
Unexploded Ordnance	UXO	Explosive objects such as bombs, mines and other munitions that did not detonate when deployed and now pose a potential risk.
United Kingdom Continental Shelf	UKCS	The areas of seabed and subsoil beyond the territorial sea (12 nautical miles from the coastline) where the UK has rights of exploration and exploitation of natural resources.

Term	Acronym	Definition
V_{ref} - 50-year extreme wind speed	V_{ref}	The extreme value of the 10-minute mean wind speed over a period of 50 years. This value (along with others) is used in IEC 61400 [21] for the classification of wind turbines.
Weighted Average Cost of Capital	WACC	The blended cost that a business pays to finance its assets, representative of all sources of capital including equity and debt.
Wind Turbine Generator	WTG	A device that converts kinetic energy from the wind into electrical energy.

3. Methodology

This section describes the methodology for Phase 1 of the assessment. Phase 1 consisted of four areas of work, the results of which are summarised later in this report (see Sections 4 to 6). These four areas of work were;

- Identification of the key engineering risks,
- Carrying out the RAG risk assessment,
- Review of FLOW technologies and their applicability in the Celtic Sea, and
- Performing relative LCOE analysis in Arup's SCALE model utilising inputs from the analysis of the key engineering risks and applicable FLOW technologies.

The methodology for each area of work is explained in more detail in the rest of this section.

Phase 2 used the outputs from Phase 1 and presented results for the PDAs. As the proposed PDAs were within the RAoS, the outputs of Phase 2 were effectively a subset of the outputs from Phase 1.

It should be noted that the scope of work and associated output is in nature high-level risk identification and qualitative. The results of the RAG assessment are based on third-party data which has not been subject to detailed review as part of this study. The results are therefore dependent on the accuracy and the completeness of the data provided by third parties and the agreed assumptions are inherently subject to uncertainty.

3.1 Identification of key engineering risks

The engineering risk assessment included 'risk identification' using a range of approaches appropriate for this level of study, including brainstorming, nominal group technique, semi-structured interviews and workshops, and high-level scenario analysis. These were driven by consideration of FLOW foundation technologies (support structures, mooring and anchoring arrangements). These approaches were undertaken by the Arup team including technical experts with input from TCE's engineering team.

The overall methodology adopted for defining the key engineering risk parameters (risk identification) can be summarised into three stages:

Stage 1: Initial desk study exercise to review the physical environmental conditions across the RAoS and to identify potential engineering risks to FLOW development, construction, and operation.

Stage 2: Identification of a longlist of engineering risk parameters.

Stage 3: Identification of a shortlist of engineering risk parameters.

3.1.1 Stage 1: Initial desk study exercise

This initial desk study exercise focussed on the ground conditions and metocean climate across the RAoS and included a review of public domain data and geospatial data sets. See Section 3.5 for a comprehensive list of data sources.

Ground Conditions

The data sources and geospatial datasets relating to the ground conditions consulted during this desk study exercise were largely obtained from British Geological Survey (BGS). BGS provide a range of offshore and onshore geological data for the UK and manage and update data alongside their research activities. BGS is regarded as an authoritative source for geological data for desk studies prior to site surveys being completed. The full list of BGS data utilised is provided in Section 3.5, references [1] to [12].

TCE commissioned desk-based studies into UXO hazard identification [13] and subsea cables [16] across the Celtic Sea AoS. Data from these studies was provided to Arup by TCE for use in this assessment.

Metocean Climate

TCE commissioned MetOceanWorks to complete a study of the metocean conditions in the Celtic Sea region [17], the H_{s_50yr} and the $V_{ref\_150m\_10mins\_50}$ datasets were used in this study.

Data from the ABPmer SEASTATES Northwest European Shelf Wave Hindcast Model [19] was utilised to create a mean annual significant wave height (H_s) dataset for use in this study. The estimated statistics are generated as the mean of all hourly H_s values in a 31-year hindcast period (January 1979 to December 2009). This was used instead of the mean wave height data from the MetOceanWorks study (above) as the MetOceanWorks data required re-processing time. A check was undertaken to ensure that this decision did not materially affect the study conclusions.

3.1.2 Stage 2: Longlist of engineering risk parameters

The insights on physical environmental conditions across the RAoS gained during Stage 1 were used to derive a longlist of engineering risk parameters.

This longlist was defined considering the influence of specific physical conditions on the technical viability and complexity of installation and operation of FLOW technologies across the RAoS, as well as conditions that may directly influence the LCOE through wind yield potential.

The longlist of engineering risk parameters is presented in Section 5.1.

3.1.3 Stage 3: Shortlist of key engineering risk parameters

The longlist of engineering risk parameters developed during Stage 2 was reduced to a shortlist of parameters to be taken forward into the RAG assessment for the RAoS.

The following basis was used to exclude risk parameters identified on the longlist from further consideration:

(a) Factors which were directly accounted for within LCOE calculations and so were already considered (reported in Section 6).

(b) Factors which are similar in nature or magnitude across all RAoS and therefore not useful in the context of this study, which aims to categorise relative risk within RAoS.

(c) Lack of available data at the time of reporting.

Section 5.1 explains the risk parameters eliminated for the reasons above and the final shortlist of key engineering risks is provided in Section 5.2

3.2 RAG assessment

Following the definition of the key engineering risks, the shortlist of engineering risk parameters was evaluated qualitatively at a high-level using a Red, Amber, Green assessment (RAG assessment). For each key engineering risk, a qualitative assessment of the overall risk level for each RAoS, and subsequent PDAs, was undertaken. In line with the high-level approach identified, risks were not analysed, quantified or evaluated in detail.

Red, Amber and Green definitions adopted for the qualitative RAG assessment were as follows:

- RED: a level of technical risk which will **likely** be complex and / or costly to mitigate.
- AMBER: a level of technical risk which **may** be complex and / or costly to mitigate.
- GREEN: a level of technical risk which is **unlikely** to be complex and / or costly to mitigate.

The RAG assessment was performed on the basis of a 2.5km-diagonal hexagon grid across the five RAoS. This is the same grid used in the SCALE modelling and enabled reporting of the RAG assessment and LCOE assessment at the same granularity. The results of the RAG assessment are summarised in Section 5.3.

Following the RAG assessment of the key engineering risks, the risks were considered in aggregate. It was determined that some risks were related so combined and maximum risks across the RAoS were analysed, as summarised in Sections 5.4 and 5.5.

3.3 Review of FLOW technologies

A high-level review of FLOW technologies and their applicability to the Celtic Sea was undertaken to provide a shortlist of FLOW technology combinations to be assessed as part of the RAG assessment and to be utilised in the SCALE model. A description of the FLOW technologies and the resulting technology combinations can be found in Section 4.

3.4 SCALE integration

As part of the Engineering Risk Assessment, LCOE modelling was carried out using Arup's proprietary offshore wind spatial planning model, SCALE. The output from this model is suitable for relative assessment of LCOE across different geospatial locations within the model boundary. The results of this analysis should be considered in the context of this assessment, input assumptions and analysis approach, and are subject to uncertainty based on the limitations of the methodology and input data. Refer to Section 6 for a detailed overview of the SCALE model methodology, input assumptions and limitations.

SCALE has been updated for the purposes of this study to model the full combination of FLOW technologies (support structures, mooring types and anchor types) summarised in Section 4. The model calculates LCOE for each hex-cell within the RAoS for each technically viable technology combination and outputs the lowest LCOE and associated FLOW technology (support structure, mooring and anchor combination).

The model also provides output on the number of viable FLOW technology combinations for a given area, highlighting areas that may be less favourable due to limitations of the physical environmental conditions for specific FLOW technologies e.g. ground conditions in some locations will preclude specific anchor types.

SCALE is run based on key user defined input assumptions which are summarised in Section 6. Further detail on the model methodology can be found in Section 6.

3.5 Data sources and references

This assessment and the results presented in this report rely on data from various third parties that has either been provided by TCE, has been licenced by Arup or is available in the public domain. The data sources utilised in this assessment can be found in Appendix A.

4. FLOW technologies

This section provides a summary of FLOW technologies and their high-level design risk characteristics relevant to the engineering risk assessment.

Section 4.1 describes the initial shortlisting of FLOW technology combinations. Each Section 4.2 to 4.6 below describes the five FLOW technology combinations agreed with TCE following the initial shortlisting. The descriptions include consideration of the potential benefits and limitations of each FLOW technology combination and, where available, examples of commercial technologies or concepts that employ each FLOW technology. Section 4.7 summarises the final combinations of FLOW technologies, including anchor types, that are considered in the modelling and assessment.

This review provides context for the RAG assessment as some of the engineering risk parameters are impacted by different FLOW technologies (see Section 5). The FLOW technologies are also considered in the SCALE modelling. Section 6.4 summarises the results of the SCALE modelling and describes the FLOW technology associated with the lowest LCOE across the RAoS and the number of viable FLOW technologies within each of the RAoS.

4.1 Longlist of FLOW technologies

A longlist of different FLOW technologies was identified from work previously completed by Arup. The technologies considered were separated into support structures, mooring types and anchor types and are summarised below.

Support structures:

- Semi-submersible.
- Monohull / Barge.
- Tension Leg Platform (TLP).
- Spar.
- Articulated or Compliant tower.

Of the five types of support structures initially identified, two were excluded from further consideration:

- Spar not considered further as water depth in all the TCE RAoS is less than 120m, which is considered the threshold for conventional spars. In addition, there are no deep water ports in the vicinity of the Celtic Sea for constructing or maintaining the support structures and wind turbine generators (WTGs).
- Articulated or Compliant tower not considered further as the technical readiness level (TRL) is low compared to other technologies.

Mooring types:

1. Catenary.
2. Semi-taut.
3. Tethered / taut.

Anchor types:

i. Gravity anchors.
ii. Drag anchors.
iii. Suction caissons.

iv. Piled anchors.

Five combinations of support structure and mooring type, based on the most common configurations in development, deployed to date and expected to be deployed in the future were agreed and considered within the engineering risk assessment and SCALE model. These combinations are shown in Table 1 below. Analysis of these combinations is presented in the following sections.

Table 1 FLOW technologies

Support structure	Semi-submersible		Monohull / barge		TLP
Mooring type	Catenary	Semi-taut	Catenary	Semi-taut	Tethered / taut
Anchor type	All types (drag, gravity, suction caisson and piled).		All types (drag, gravity, suction caisson and piled).		Gravity, suction caisson and piled.

4.2 Semi-submersible + catenary

This concept uses a semi-submersible support structure with catenary mooring lines.

Semi-submersible support structures have distributed buoyancy, usually large columns or submerged pontoons linked by connecting bracing. The platform's stability is enhanced by the wide-spread distribution of its buoyancy units.

Catenary moorings, in their simplest form, utilise free hanging chain lines without additional weights or buoyancy units. The mooring length must be significantly greater than the water depth. The anchor points are subjected to horizontal forces and are therefore suitable for simple anchors which only need to withstand horizontal loads e.g. drag anchors.

This concept is feasible in water depths greater than 50m.

Example products are provided below.

Table 2 Example semi-submersible + catenary products

Technology	WTG Capacity	Support Structure	Moorings	Description
WindFloat	9.5MW	Semisub	Three catenary mooring lines.	Three radial columns and truss solution with the turbine supported on one of the outer columns.
VolturnUS	15MW	Semisub	Three catenary mooring lines.	Four-column, three radial and one central with the turbine on the central column.
OO-Star	11MW	Semisub	Three catenary mooring lines.	Four-column design, three radial and one central, connected by rectangular pontoons towards the lower part of the hull. The WTG is supported on the central shaft.

4.3 Semi-submersible + semi-taut

This concept uses a semi-submersible support structure with semi-taut mooring lines.

As noted in 4.2 semi-submersible support structures have distributed buoyancy, usually large columns or submerged pontoons linked by connecting bracing. The platform's stability is enhanced by the wide-spread distribution of its buoyancy units.

Semi-taut moorings are similar to catenaries but utilise a section of taut rope connected to a gravity-based chain line. The chains can be self-weighted or have additional clump weights attached. Connecting components are required to connect the rope and chain portions of the line.

The anchor points are subjected to horizontal forces and therefore are suitable for anchors which can be configured to only require horizontal support and hence are able to use low cost technology drag anchors in suitable soil conditions.

This concept is suited to water depths greater than 50m.

Example products are provided below.

Table 3 Example semi-submersible + semi-taut products

Technology	WTG Capacity	Support Structure	Moorings	Description
PelaFlex	TBC	Semisub	Tensioned moorings.	Tetrahedral design comprising seven primary steel tubular components and three distinct parts.

4.4 Monohull / barge + catenary

This concept uses a monohull / barge support structure with catenary mooring lines.

The monohull / barge support structure is a simple floatation system where the buoyancy is evenly distributed. Unlike a semi-submersible, that is constructed of several linked pontoons, a monohull / barge has a single hull structure that penetrates the water line.

Refer to Section 4.2 for a description of catenary moorings.

This concept is feasible in water depths greater than 50m.

No current examples of monohull / barge + catenary moorings are available.

4.5 Monohull / barge + semi-taut

This concept uses a monohull / barge support structure with semi-taut mooring lines. Refer to Section 4.4 for a description of the monohull / barge and Section 4.3 for a description of semi-taut moorings.

This concept is suited to water depths greater than 50m.

Example products are provided below.

Table 4 Example barge + semi-taut products

Technology	WTG Capacity	Support Structure	Moorings	Description
Damping Pool	TBC	Monohull / barge	Six semi-taut mooring lines (synthetic / nylon).	Square ring-shaped hull with a moonpool.
Sevan SWACH	14MW	Monohull / barge	Semi-taut.	Cylindrical small waterplane area hull (moonpool).
Triwind Floater	15MW (TBC)	Monohull / barge	Semi-taut, composed predominantly of synthetic ropes.	Triangular concrete base with compartments / cells.

4.6 Tension Leg Platform + taut

This concept uses a tension leg platform (TLP) support structure with taut mooring lines or tendons.

TLPs are semi-submerged buoyant structures with taut vertical tendons that secure the foundation to the seabed via anchors. The TLP obtains its stability from the mooring system, which provides high stability in operation.

A taut mooring system is pre-tensioned with vertical tendons. Taut moorings are subjected to both horizontal and vertical forces, therefore require anchors that can withstand vertical loads e.g. gravity, suction or piled anchors. The taut mooring system has greater stiffness than both semi-taut and catenary moorings and therefore has good stability in operation, but high anchor loads.

Although there is less information and precedence regarding the depth limit for TLPs supporting WTGs it is likely to be similar to, or slightly greater than that of semi-submersibles and monohull / barges at around 60m to 70m.

Example products are provided below.

Table 5 Example TLP + taut products

Technology	WTG Capacity	Support Structure	Moorings	Description
SBM TLP	TBC	TLP	Inclined tensioned legs.	Three columns, primarily truss structure platform.
GICON-SOF	TBC	TLP	Taut mooring lines.	Four columns with smaller tubular components to support the turbine. A concrete gravity base is incorporated to enable self-installation of the mooring system.
Eco TLP	7MW	TLP	Tension legs.	Circular hull with a gravity anchor that enables self-installation of the mooring system.

4.7 FLOW technologies summary

The advantages and disadvantages of the combinations of FLOW technologies are summarised in Table 6 below. These FLOW technology combinations have been utilised in the remainder of this assessment, including the engineering risk assessment and SCALE modelling. Specific elements of these combinations, such as anchor type are discussed in the context of the applicable engineering risks in Section 5 and the combinations found to be viable and the lowest cost in the SCALE model are discussed in Section 6.

Table 6 Advantages and disadvantages of FLOW technology combinations

<table>
<tr><th></th><th>Semi-submersible + catenary</th><th>Semi-submersible + semi-taut</th><th>Monohull / barge + catenary</th><th>Monohull / barge + semi-taut</th><th>TLP + taut</th></tr>
<tr><td>Advantages</td><td colspan="2">Semi-submersible support structures have shallow draught, therefore can be assembled, including the WTG, in a dock or port and transported to site using conventional tugs.

Semi-submersible support structures remain stable when un-moored so can be towed back to dock or port for maintenance.

This technology experiences only low and horizontal anchor loads, hence ability to use low cost technology drag anchors in suitable soil conditions.</td><td colspan="2">Monohull / barge support structures have shallow draught, therefore can be assembled in a dock or port, including the wind turbine generator, and transported to site using conventional tugs.

Monohull / barge support structures remain stable when un-moored so can be towed back to dock or port for maintenance.

Monohull / barge support structures can be relatively simple to fabricate and hence can potentially facilitate local content more readily.

Low and horizontal only anchor loads, hence ability to use anchors which have low sensitivity to soil conditions.</td><td>TLPs have a light support structure so are likely to be lower cost than other structures.

TLPs have shallow draught therefore can be assembled in a dock or port, although are not sufficiently stable to have their WTGs fitted in a dock or port.

Taut moorings have a small overall area footprint and limit motion, facilitating the lighter platform design.</td></tr>
<tr><td rowspan="2">Disadvantages</td><td colspan="2">Semi-submersible support structures are large structures which generally require more material, compared with tension leg platforms, and more complex fabrication, compared with monohulls / barges.

Although semi-submersible support structure stability is good, there can be significant motion in extreme conditions requiring flexible mooring and electrical cabling.</td><td colspan="2">Monohull / barge support structures are less stable than platforms with distributed buoyancy such as semi-submersibles and therefore experience more pitching motions in extreme conditions generating larger accelerations and forces in the turbine and tower.

Monohull / barge support structures can experience significant motion requiring particularly flexible mooring and electrical cabling.</td><td>TLP support structures are relatively complicated and require more sophisticated mooring and anchors.

A specialised installation vessel may be required (design dependent) to keep the TLP stable during transportation.

Since the TLP support structure is not inherently stable without its moorings, unless supplementary buoyancy is added, the WTG will probably need to be installed on location using a crane vessel. The same applies for major maintenance operations.

The taut mooring system requires anchors which can resist constant vertical loads and therefore the sensitivity to soil conditions is high.</td></tr>
<tr><td>Catenary moorings have a large overall area footprint.</td><td>Semi-taut moorings have a large overall area footprint however smaller than catenaries.</td><td>Catenary moorings have a large overall area footprint.</td><td>Semi-taut moorings have a large overall area footprint however smaller than catenaries.</td><td></td></tr>
</table>

5. Engineering risk assessment

This section summarises the results of the engineering risk assessment. As described in Sections 3.1 and 3.2, this comprised two areas of work, namely defining the key engineering risks, that would aid in relative risk assessment across the RAoS, and then assessing the RAoS against those key engineering risks. Section 5.1 presents the initial assessment of the longlist of engineering risk parameters and describes those risk parameters that were eliminated from further consideration in the engineering risk assessment. Section 5.2 summarises the shortlist of key engineering risks that were investigated across the RAoS. Sections 5.3 to 5.6 present the results of RAG assessment of the key engineering risks across the RAoS including consideration of the combined and maximum risks (comprising an aggregate assessment of the key engineering risks) across each of the RAoS.

The results of the engineering risk assessment for the PDAs utilises the same methodology described in this section and the results of the PDA assessment can be found in Section 7.

5.1 Longlist of engineering risk parameters

5.1.1 Longlist

A longlist of engineering risk parameters was compiled in agreement with TCE considering the physical characteristics of the RAoS that may present a technical risk to the development of a FLOW project within the RAoS. The longlist of engineering risk parameters considered is summarised in Table 7 Longlist of engineering risk parameters below.

Table 7 Longlist of engineering risk parameters

Category	Engineering risk parameter	Data reference
Metocean conditions that influence the technical viability and complexity of installation and operation, as well as directly influencing the LCOE through wind yield potential.	Average wave height, the wave loading for installation and operations.	[18]
	One in 50-year extreme wave height, the design wave loading.	[17]
	Wind speed, both one in 50-year extreme wind speed, the structural design wind speed, and the average wind speed for the Annual Energy Performance (AEP) calculation.	[18]
	Tidal range.	[18]
	Current speed.	[18]
Geology and ground conditions that influence the technical viability and complexity of installation.	Bathymetry.	[20]
	Depth to bedrock.	[8]
	Bedrock lithology.	[7]
	Seabed mobility.	[1]
	Seabed slope.	[10]
	Quaternary deposits lithology.	[9]
	Shallow gas.	[11]
Other site conditions that influence installation and operation, that influencing LCOE rather than presenting a site specific engineering risk.	Distance to shore.	

Category	Engineering risk parameter	Data reference
Physical infrastructure that influences the technical viability, risk of installation and operation.	Unexploded ordinance (UXO).	[14]
	Cables.	[16]

Of these engineering risk parameters, the longlist was assessed by analysing the relevant data (see references above) at a macro level across the RAoS and a number of the engineering risk parameters were eliminated from further consideration.

The parameters that were not included in the shortlist of engineering risk parameters were either directly accounted for within LCOE calculations and so were already considered within that metric which is reported on later in this report (see Section 6), or alternatively were not considered site specific risks when considering the RAoS, and therefore would not be beneficial in a relative risk assessment across the RAoS. A summary of each of these engineering risk parameters is provided in the sections below.

5.1.2 Eliminated risk parameters: factors influencing LCOE

There were a number of factors included within the SCALE model that inform the LCOE calculation, but were not considered to be key engineering risk parameters, so were not considered standalone within the RAG assessment.

Distance to shore

The distance to shore, for both nearest ports for construction and operation and nearest primary substation into which the transmission cable connection is made, informs the LCOE calculation within the SCALE model and so any cost increase associated with increased distance from shore was accounted for in the LCOE calculation.

Wind Resource

Wind speed informs the LCOE calculation within the SCALE model due to the influence on Annual Energy Production (AEP) and there is therefore no need to additionally consider the risk associated with low wind resource.

Quaternary deposits lithology

The quaternary deposits summary lithology across the Celtic Sea RAoS is shown in Figure 4. The mapping of these deposits largely mirrors the trends of depth to bedrock, with the majority of areas with bedrock at less than 20m depth being overlain by the same quaternary deposit.

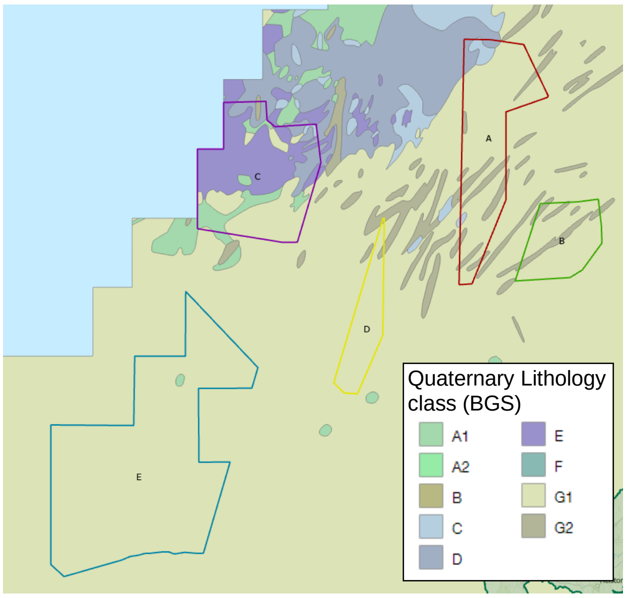


Figure 4 Quaternary deposits summary lithology (from data in [1])

A brief commentary of the main lithologies identified and the potential engineering risks is provided below.

Quaternary Lithology class –1 – Undifferentiated

The dominant lithology across RAoS A, B, D and E is the "G1 – Undifferentiated" category, as introduced by the BGS in the 2015 update of the Geological Factor Maps [3]. These deposits are anticipated to be characterised by "*frequent changes in lithology, including soft muds, gravel, sands*" [3]. Review of the BGS 1:250k scale Quaternary Geology map of the North Celtic Sea [4] and the 1:1M scale map of Quaternary Geology around the UK [5] provides no further insight into the classification and nature of these deposits.

The undifferentiated nature of these deposits makes them extremely challenging to define in engineering terms until data from site specific investigations is made available.

With respect to anchor feasibility, the extremes of the potential material types in this lithology group should be considered. The presence of loose or very soft deposits will be beneficial for the installation of drag anchors and suction caissons (where sufficient thickness is available). The low strength will however impact the holding capacity of anchors and necessitate larger (or a greater number of) anchors. At the other extreme, the presence of heterogenous deposits of dense sand or hard clay is likely to significantly limit the penetration depth and hence holding capacity of drag anchors and suction caissons and increase the risk associated with installation of driven piles.

The feasibility of drilled and grouted anchors is unlikely to be affected by this quaternary type. Higher strength deposits will be beneficial with respect to reducing anchor size. Gravity bases, which are only assumed feasible where the quaternary deposits are shallow, are also assumed to be largely unaffected.

Quaternary Lithology class G2 – Undifferentiated

Localised incisions of "G2 – Undifferentiated" quaternary deposits are identified across RAoS A (southern half), RAoS B (north-western half) and at the northern tip of RAoS D. These correspond to localised areas of deeper bedrock. The BGS have classified this quaternary deposit type as "*late glacial deposits that infill channels…They are usually sandy muds but may include muddy sands or even sand but rarely any gravel… They are usually normally consolidated as they have not been loaded by ice and have remained lacustrine or marine since deposition. Their strengths increase with depth due to gravitational loading*" [3].

Review of the BGS 1:250k scale Quaternary Geology map of the North Celtic Sea [4] indicates that these deposits are largely incisions of the undivided Western Irish Sea Formation.

These deposits are likely to be suitable for the installation of drag anchors, suction caissons and driven piles. Holding capacity may be limited by the low strength of the material, necessitating larger (or a greater number of) anchors.

Drilled and grouted piles would be unsuitable in the areas of the site where these incisions of softer material are present. This may lead to a scenario where mixed anchor solutions are required.

Quaternary Lithology class E – Firm to hard interbedded mud and sand

This quaternary lithology is limited to the northern half of RAoS C, where there is a notable increase in depth to bedrock and the seabed environment is dominated by presence of the Celtic Deep Trough. This broad trough feature is between 20km and 50km wide, extending south-west from St George's Channel to the Celtic Deep at approximately 51°N. The quaternary deposits in this trough are generally in excess of 100m thick, with localised thicknesses in excess of 200m in infilled incisions [1]. Review of the BGS 1:250k scale Quaternary Geology map of the North Celtic Sea [4] indicates that these deposits primarily comprise the Bedded and Incision Infill Facies of the Caernarfon Bay Formation and the undivided deposits of the St George's Channel Formation.

This material type is generally anticipated to be suitable for most anchor types with respect to installation and holding capacity, unless harder bands of material dominate. In this scenario, installation of driven piles, suction caissons and drag anchors may become challenging.

Quaternary Lithology class D – Soft mud

There is a limited area of soft mud in the southern half of RAoS C. The considerations with respect to anchor feasibility are as described for 'G2 – Undifferentiated'.

Quaternary Lithology class A1 – Firm to hard diamict

There is a limited area of diamict along the north and east boundaries of RAoS C. This lithology, characterised by a potential presence of cobbles and boulders in a generally mud dominated sediment [2], creates a challenging and highly uncertain installation environment for all foundation types.

Driven piles and suction caissons are unlikely to be a feasible solution in this material due to the risk of refusal prior to achieving design penetration depths. There is a high risk that drag anchors would be unable to achieve sufficient embedment to derive the necessary holding capacity. The presence of boulders increases the risk to progress of drilled piles.

Gravity bases will be the least affected by the presence of this material, assuming suitable bearing strength is available.

Summary

The effect of quaternary deposit on anchor viability and sizing was considered explicitly in the LCOE calculation completed in SCALE. On this basis, the quaternary deposits were not included as part of the shortlist of engineering risks.

5.1.3 Eliminated risk parameters: physical factors not considered site specific

The below parameters were considered as part of the longlist of engineering risk parameters, but were not taken forward into the RAG assessment as they were not considered site specific risks relevant for the RAG assessment, the aim of which was to provide a relative risk assessment across the RAoS. A broad overarching summary of each of these parameters is provided below.

Seabed slope

Seabed slope may influence anchor selection, in particular for gravity base and suction caisson anchors which are generally only considered suitable for slopes with gradients less than 5 degrees.

The BGS have produced a rugosity layer within their geological factor maps, updated in 2015 to a scale considered suitable for assessing the roughness of an area of 75m x 75m. Rugosity has been categorised by the BGS as Red, Amber or Green, as shown in Figure 5 for the Celtic Sea RAoS (from data in [10]). The significant majority of the RAoS are shown as low rugosity (green).

The dataset provides a good indication of overall sea slopes but is inherently limited by the resolution of the data used to derive the rugosity. At the scale of a suction caisson anchor (typical diameters could be circa 5m), local seabed slopes in excess of 5° may not be detected within the BGS data.

On the basis of the low rugosity rating across all RAoS, and the lack of data to further interrogate at a more local scale, this risk was not carried forward to the shortlist.

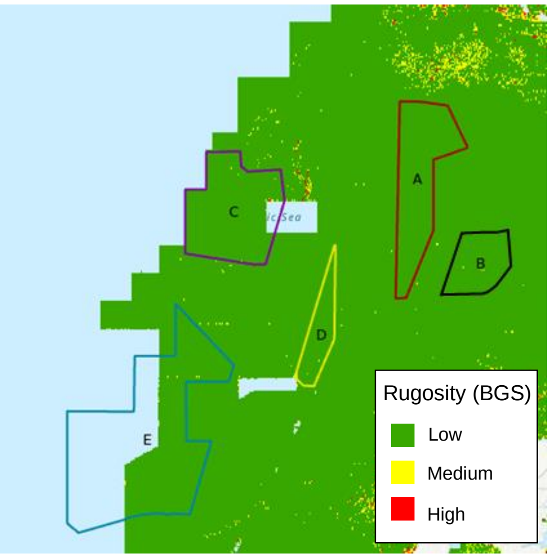


Figure 5 Rugosity across the RAoS (from data in [1])

Seabed mobility

Mobile seabed sediments present a potential risk to all anchor types due to exposure (generally the most critical) or burial of anchors after they have been placed. The risk is considered highest for gravity base and suction caisson anchors.

The BGS have prepared a dataset with "Geological Indicators of Sediment Mobility" [1]. No indicators of sediment mobility have been identified in the dataset within the RAoS.

On the basis of the low rating across all RAoS, and the lack of data to further interrogate at a more local scale, this risk was not carried forward to the shortlist.

Tidal range

Within the MetOceanWorks report commissioned by TCE [17] the tidal regime in the Celtic Sea is summarised as below.

"*The tidal range within the study area exceeds 9m towards the Bristol Channel, decreasing to a little over 4m offshore, such that the entire region is macro-tidal (having tidal range greater than 4m). The large tidal range within the Bristol Channel and Severn Estuary is caused by amplification of the tidal wave within the funnel-shaped estuary.*

Due to the proximity of a degenerate tidal amphidrome near Courtown in Ireland, some of the northern parts of the study zone experience a 'standing wave' tidal system. As a result, the timing of peak current speeds there are closer to high or low water than they are to mid tide, when the rate of change of water level is at a maximum."

The Celtic Sea features a larger tidal range than other locations around the UK, so note should be taken within site specific risk assessments of this environmental factor and incorporated or planned for within designs and installation plans. Whilst the impact of tidal range is recognised as a factor that must be considered during site development, due to the limited variance in the tidal range over the RAoS, and therefore the limited impact of tidal range within a comparative risk assessment across the different RAoS, this risk was not included in the shortlist of key engineering risks.

Current speed

Within the MetOceanWorks report commissioned by TCE [17] the current regime in the Celtic Sea is summarised as below.

"*The current regime is relatively benign, except for the strong currents around St. David's Head in Wales and Ushant in France.*"

The current regime should be studied further during site specific studies and considered as part of the engineering assessment and design. As there was limited variance in the current regime across the RAoS, and therefore limited impact of current regime within a comparative risk assessment across the different RAoS, this risk was not included in the shortlist of key engineering risks.

5.1.4 Eliminated risk parameters: additional broad geospatial risk datasets

The below risks were considered as part of the longlist of engineering risk parameters, but were not taken forward into the RAG assessment as they were not considered site specific risks relevant for the RAG assessment, the aim of which was to provide a relative risk assessment across the RAoS. A broad overarching summary of each of these risks is provided below.

UXO risk rating

A UXO Hazard Assessment has been completed for the Celtic Sea AoS 1-5 by Ordtek on behalf of TCE [13].

Data from the Ordtek UXO desk study [14] was incorporated to produce a RAG classification of UXO hazards across the search areas. RAG descriptions from [13] are replicated in Table 8 and the RAG zones shown against the RAoS in Figure 6.

Table 8 UXO Hazard RAG descriptions (from [13])

Risk rating	Definition
RED	The 'red zone' is defined as an area displaying significant UXO contamination, particularly from items such as mines, bombs and projectiles.
AMBER	The 'amber zone' is defined as an area displaying moderate UXO contamination. Typically, this is a designated safety buffer around convoy routes and surrounding live firing and bombing areas. In addition, it accounts for low-density larger, non-sensitive items such as WW1 sea mines.
GREEN	The 'green zone' is defined as a residual level of contamination not from a direct known source of UXO. It should be noted that there is still a risk due to the level of military activity over the years within the Celtic Sea.

In summary, based on Ordtek's desk study:

- UXO presents a potential risk to the development of FLOW in the Celtic Sea, principally due to the UXO residue from both World War One (WW1), World War Two (WW2), and modern military training and practice exercises.
- RAoS A, B and C are all located fully within the red UXO risk zones. The hazards identified within all these areas include the presence of WW2 Minefields and Wrecks of Military Interest. In RAoS A and B, the presence of WW2 Mine Lays is also identified.
- RAoS D spans the boundary of the green and red UXO risk zones, with WW2 Minefields identified in the north-eastern tip of the RAoS.

- RAoS E is the only area fully within a green UXO risk zone, with the only identified hazard within this area being the presence of eight to nine Wrecks of Military Interest.

A full and detailed UXO Risk Assessment is required to assess the risk to development of FLOW in the RAoS, considering in detail the findings from the UXO hazard assessment and the environmental and ground conditions across the sites. As recommended in [13], this should include a Risk Mitigation Strategy to be implemented during development and installation phases and the technical specification for any specialist geophysical surveys required. Due to work already completed by Ordtek and the lack of any additional information at the time of the assessment, this risk was not taken forward to the shortlist of key engineering risks.

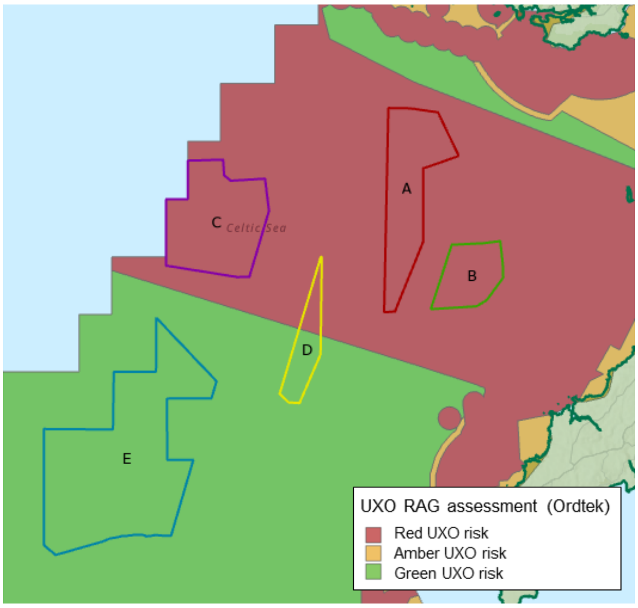


Figure 6 RAG assessment of UXO hazard [14]

Cable routes

TCE provided a geospatial dataset of telecommunication cables across the Celtic Sea with RAG categorisation. The rationale for RAG characterisation is based on the likelihood of the cables still being utilised during the anticipated operational phase of Round 5 projects. Figure 7 shows the cables crossing the RAoS without the RAG rating. In general, it is anticipated there will be an exclusion zone for anchors around the cables. The interaction of catenary mooring lines and cables also requires further consideration, particularly in regions where cables are at the seabed surface rather than trenched and there is greater risk of interaction.

The number of cables crossing each of the RAoS is summarised in Table 9 to enable a comparison of the relative risks across each site. Cables at the RAoS boundaries have not been included in the count.

Due to the absence of any additional data on the cable routes at the time of the assessment, this risk was not taken forward to the shortlist of key engineering risks. It is recommended that the European Subsea Cables Association Guideline No.6 [15] is consulted in relation to managing developments in the proximity of existing cable routes.

Table 9 Number of cables crossing each RAoS

RAoS	Total
A	6
B	4
C	2
D	7
E	5

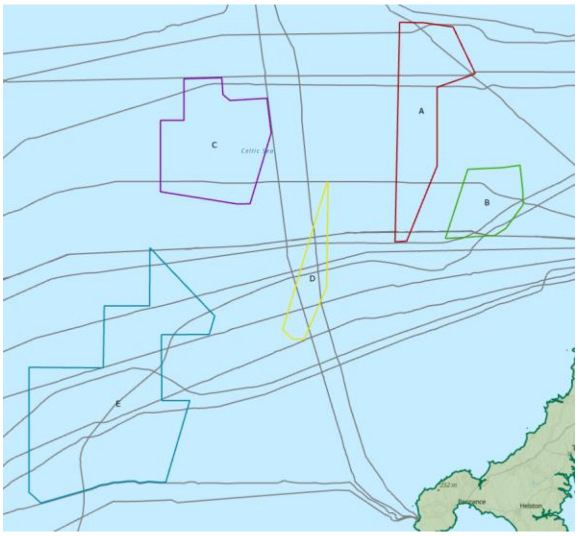


Figure 7 TCE Celtic Sea Telecoms Cables

5.2 Final shortlist of key engineering risks

The remaining engineering parameters in the longlist gave the final shortlist of key site specific engineering risk parameters. This shortlist of key engineering risk parameters represented risks that may vary across the RAoS and provide a differentiation in the relative risk across the RAoS. The shortlisted engineering risk parameters taken forward into the RAG assessment for the RAoS were as follows:

A. Seabed depth.

B. Depth to bedrock.

C. Bedrock lithology, specifically strength of bedrock for anchor installation.

D. Wave loading for installation (average wave height).

E. Wave loading for O&M (average wave height).

F. Metocean conditions for structural feasibility (extreme wave and wind conditions).

G. Shallow gas.

Red, Amber and Green definitions adopted for the qualitative RAG assessment were as follows:

- RED: a level of technical risk which will **likely** be complex and / or costly to mitigate.
- AMBER: a level of technical risk which **may** be complex and / or costly to mitigate.
- GREEN: a level of technical risk which is **unlikely** to be complex and / or costly to mitigate.

5.3 RAG assessment of key engineering risks

This section summarises the results of the RAG assessment of the shortlisted key engineering risks, based on assessment of the relevant risk parameters. Each of the seven key risks identified was given a red, amber, green rating which is defined in each section below. The maps in each section show the risk rating for each hex-cell across the five RAoS. The overall risk rating for each RAoS was based on the average risk rating across all the hex- cells within each RAoS.

5.3.1 Seabed depth

Seabed depth is an important factor in selecting the most appropriate type of support structure for an offshore WTG.

Seabed depth of 50m is considered the lower limit for the technical feasibility of floating wind, although deeper water is likely to be required before floating support structures are commercially viable (compared to alternative fixed wind structures), particularly when considering the larger WTGs under development.

All RAoS have depth between 70m and 120m [20]. This depth range means that the only common floating support structure which was not considered feasible is the conventional spar which typically requires water depth greater than 120m. (Note that spar and articulated or compliant tower floating technologies were ruled out of the technology review previously, see Section 4.1).

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 10.

Table 10 Seabed depth – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to seabed depth	Rationale with respect to seabed depth
RED	< 50m	Limit below which floating support structures are not considered feasible for WTGs.
AMBER	50m – 120m	Depth range where semi-submersible, monohull / barge and TLP support structures are considered feasible.
GREEN	> 120m	Depth above which all types of floating support structure are considered feasible.

The resulting RAG map, based on data from [20], is shown in Figure 8.

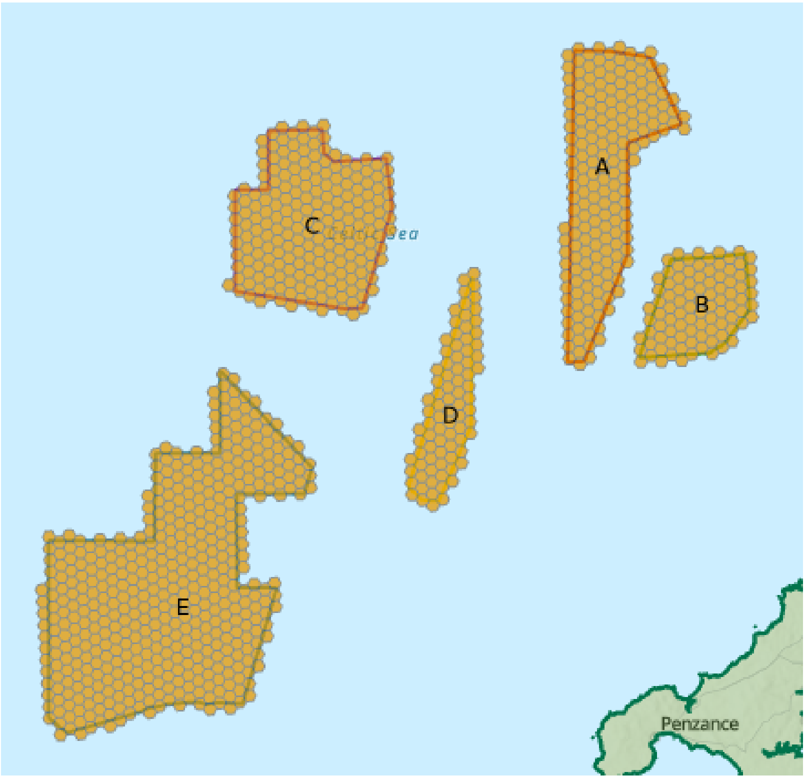


Figure 8 Seabed depth – RAG risk rating by hex-cell

Table 11 Seabed depth – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

5.3.2 Depth to bedrock

Bedrock across the Celtic Sea RAoS is generally shallow, with large areas less than 5m below the seabed and the majority being less than 20m below seabed [8]. The depth to bedrock is a critical parameter in determining the range of potentially feasible anchor types. The presence of bedrock within a few metres of the seabed is likely to limit the choice of anchor types to piled and gravity anchors. Driven piles may be feasible in weaker rock types and, in stronger rock types, costly drilled and grouted solutions may need to be employed. This is discussed as a separate risk item in Section 5.3.3. The simplest and lowest cost anchor types, specifically drag anchors and suction caissons, require a minimum thickness of quaternary deposits and will not be feasible in areas of shallow bedrock.

The depth to bedrock where suction caissons, drag anchors and driven piles may start to become feasible will depend on several factors, most critically the anchor load and the nature of the quaternary deposit lying on top of the bedrock. The anchor load will itself be a function of technology type, mooring type and layout, water depth, turbine type and metocean conditions. It is generally anticipated that around 20m quaternary thickness will be required for drag anchors and suction caissons, although the exact requirements will depend on the type of quaternary deposit and the anchor design.

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 12.

Table 12 Depth to bedrock – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to depth to bedrock	Rationale with respect to depth to bedrock
RED	< 5m	Limited to drilled pile or gravity anchors. Driven piles may be feasible in weak rock.
AMBER	5m – 20m	Suction caissons and drag anchors start to become feasible at upper end of depth range.
GREEN	> 20m	All anchor types become feasible.

The resulting RAG map, based on data from [8], is shown in Figure 9.

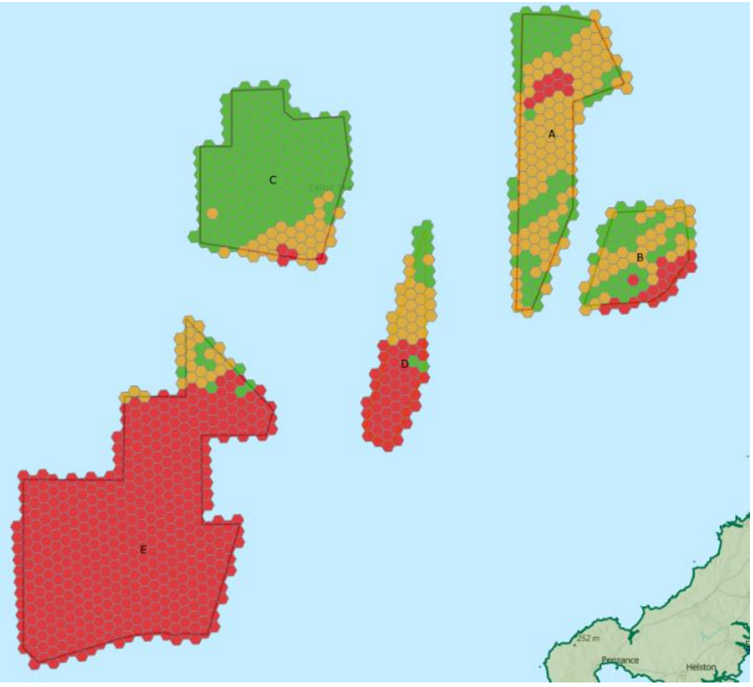


Figure 9 Depth to bedrock – RAG risk rating by hex-cell

Table 13 Depth to bedrock – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

Note, the assessment of anchor feasibility was on basis of depth to bedrock only. Feasibility also needs to consider the quaternary deposit lithology (see Section 5.1.2) and the strength of the bedrock (see Section 5.3.3).

5.3.3 Strength of bedrock for anchor installation

Much of the Celtic Sea RAoS (except for RAoS C) is anticipated to be underlain by relatively shallow bedrock. In areas shown as amber and red in Figure 9, there is a moderate to high risk of needing piled anchor solutions where drag anchors and suction caissons become unfeasible.

It is noted that the structural geology is complex throughout the RAoS including faulting and folding of the bedrock both at rockhead and at depth [6], particularly in RAoS A and C. Areas of salt piercement are also identified in RAoS A and C [6]. This setting can lead to lateral and vertical variation in bedrock strength and composition in the vicinity of these features. Site specific geophysical investigations and follow-on geotechnical field campaigns should enable the complexity of the structural geology to be better understood, specifically at depths relevant to anchor installation.

The strength of the bedrock will influence both the method of pile installation (i.e. drilled or driven) and the time and hence cost of installation. In weak rocks, such as chalk and weak mudstone, it may be feasible to install piles using conventional driving techniques or a drive-drill-drive process. The ability to install by driving will depend on the specific characteristics of the rock (including strength, fracture state and degree of weathering) as well as the lateral and vertical variation of these properties. The potential presence of flint bands in the chalk underlying large areas of the RAoS may also influence the feasibility of different installation techniques for piles in chalk. The effect of installation method on in-place capacity will also require consideration, in particular for chalk.

Beyond the limits of installation by driving, pile installation by drilling and grouting is feasible in weak to moderately strong rocks. Progress rates and hence cost of drilling are likely to be significantly impacted by the strength of the material. In high strength rocks, including igneous and metamorphic lithologies, pile installation by drilling and grouting may become prohibitively expensive.

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 14.

Table 14 Strength of bedrock for installation – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to strength of bedrock for anchor installation	Rationale with respect to strength of bedrock for anchor installation
RED	Hard rock types: Igneous, Palaeozoic sedimentary, Metamorphic.	Drilled and grouted piles. Challenging environment for drilling. Relatively low drilling progress rate.
AMBER	Medium rock types: Mesozoic sandstones and limestones, Mesozoic interbedded, Tertiary sandstones and limestones.	Drilled and grouted piles. Normal drilling progress rate.
GREEN	Weak rock types: Chalk, Mesozoic mudstones, Tertiary interbedded.	May be feasible to install piles by driving or DDD techniques. If installation is by drilling, relatively high progress rate.

The resulting RAG map, based on data from [7], is shown in Figure 10.

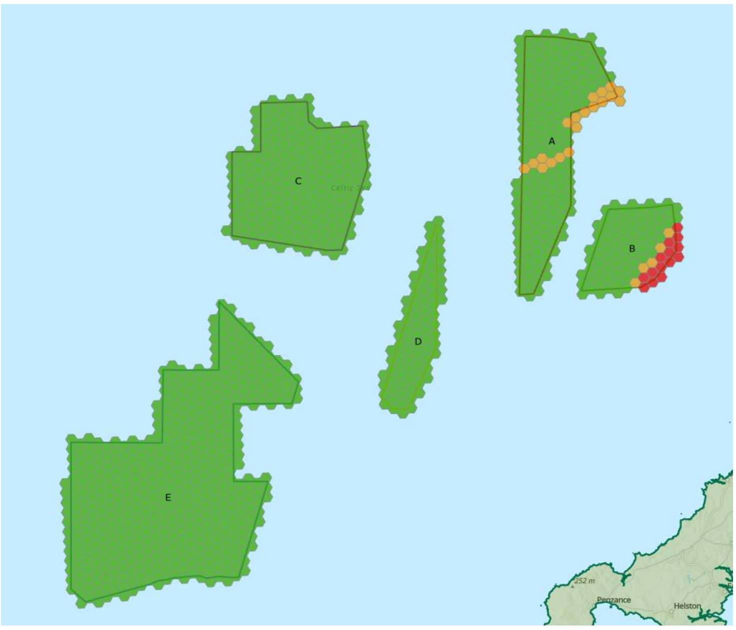


Table 15 Strength of bedrock for anchor installation – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

Figure 10 Strength of bedrock for anchor installation – RAG risk rating by hex-cell

Effect of bedrock strength on anchor capacity

Note that the risk ratings presented in this section relate to anchor installation only, and not the impact that bedrock strength will have on anchor capacity. In general, there is a correlation between the resistance during installation and the strength during operation, where higher strength rocks will contribute more to anchor capacity than lower strength rocks and will present higher resistance during installation by either driving or drilling.

The relationship between bedrock strength and anchor capacity will be further influenced by the anchor type and predominant direction of loading. For example, the design of gravity anchor founded on bedrock is likely to be largely insensitive to the strength of the bedrock in any loading direction, whereas the capacity of a piled anchor under predominantly vertical loading will be strongly influenced by the strength of the rock, up until the point where the strength of the steel (or some other factor) governs the design. The capacity of anchor piles under predominantly lateral loading (for example for catenary or semi-taut mooring systems) is likely to be less sensitive to the strength of the bedrock than axially loaded piles.

Special attention is required for piled anchors installed in chalk, which underlies large areas of the Celtic Sea RAoS, with respect to both anchor capacity and installation technique. Chalk can undergo significant degradation in strength during both installation and subsequently in cyclic loading during operation. This is likely to result in the requirement for significantly larger piled anchor dimensions (or increased number of piles), particularly for piles loaded predominantly in tension (e.g. for TLPs), when compared with other non-chalk rock types of comparable in-situ strength. As the risk rating presented in this section relates to strength of bedrock for anchor installation only, chalk is rated as green.

5.3.4 Wave loading for installation

A sea state below a certain significant wave height will be required to install the support structures and, if installed separately, the WTGs.

Monohull / barge and semi-submersible support structures are likely to have their WTGs installed in a port or dock and then be towed to the site to be connected to their mooring systems as a complete unit.

TLP support structures are not sufficiently stable to have their WTGs installed before they are connected to their mooring tendons unless additional buoyancy is added. Therefore, the WTGs are likely to be installed on TLPs on location at the site and hence a sea state below a certain significant wave height will also be required for the floating cranes to install the WTGs.

A weather window, where the significant wave height is below the installation threshold for a sufficient duration, is required for installation of the support structures and WTGs. Mean annual significant wave height (calculated from [19] as the mean of all the hourly measurements within the 31-year hindcast period of the dataset) was used as a proxy for this subjective installation assessment. (More robust risk categorisation could feasibly be undertaken based on time series-based weather window analysis and cost optimisation – but this was out of scope for this high-level assessment).

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 16.

Table 16 Wave loading for installation – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to mean annual significant wave height	Rationale with respect to mean annual significant wave height
RED	> 2.5m	Harsh mean sea state: higher mean annual significant wave height than previous UK leasing rounds.
AMBER	2m – 2.5m	Moderate mean sea state. Weather windowing for some more sensitive installation activities will be challenging.
GREEN	< 2m	Relatively benign mean sea state, considered suitable for weather windowing most operations.

The resulting RAG map, based on data from [19], is shown in Figure 11.

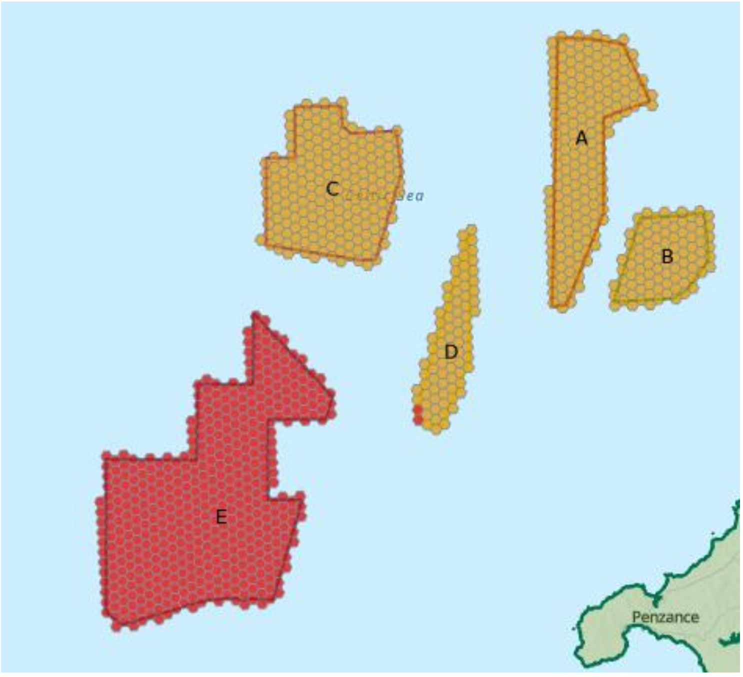


Figure 11 Wave loading for installation – RAG risk rating by hex-cell

Table 17 Wave loading for installation – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

5.3.5 Wave loading for O&M

A sea state below a certain significant wave height will be required to de-couple the support structures (semi-submersible or monohull / barge) from their mooring systems to enable them to be towed back to a port or dock for the completion of major repairs or major maintenance operations.

As major repairs or major maintenance operations on TLP support structures and their WTGs are likely to be completed on location at the site then a sea state below a certain significant wave height will be required for the floating cranes required for these operations.

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 18, using the same thresholds as in the previous section.

Table 18 Wave loading for O&M – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to mean annual significant wave height	Rationale with respect to mean annual significant wave height
RED	> 2.5m	Harsh mean sea state: higher mean significant wave height than previous UK leasing rounds.
AMBER	2m – 2.5m	Moderate mean sea state. Weather windowing for some more sensitive installation activities will be challenging.
GREEN	< 2m	Relatively benign mean sea state, considered suitable for weather windowing most operations.

The resulting RAG map, based on data from [19], is shown in Figure 12.

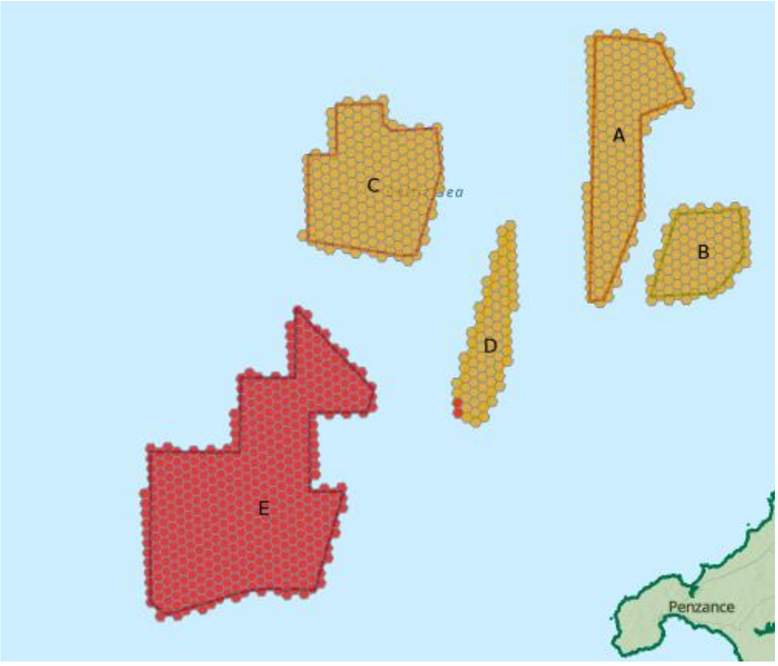


Figure 12 Wave loading for O&M – RAG risk rating by hex-cell

Table 19 Wave loading for O&M – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

Although the above assessment based on mean annual significant wave height indicates useful variation across the RAoS, there is limited evidence that a mean annual significant wave height above 2.5m is categorically different in terms of resulting cost or complexity (for either installation or O&M) compared to mean annual significant wave height 2.0-2.5m. This should be borne in mind when interpreting final results.

5.3.6 Metocean conditions for structural feasibility

The harshness of the metocean conditions at a particular location will influence the cost and ultimately the feasibility of a particular support structure and mooring configuration.

The metocean conditions considered most relevant high-level to the structural feasibility of the support structure and mooring combination are the extreme wave and extreme wind conditions.

The governing criteria is based on ORE Catapult's Mooring and Anchoring Systems report [22] as shown in Table 20, for extreme wave height (H_{s_50yr}) and the IEC 61400 wind turbine classes [21] as shown in Table 21 for wind speed (V_{ref}). The resulting RAG criteria is shown in Table 22.

Table 20 50-year extreme wave height for potential FLOW project conditions

Site conditions	50-year extreme significant wave height H_{s_50yr} (m)
Benign	< 13
Moderate	13 - 16
Exposed	> 16

Table 21 Classification of wind turbines from IEC-61400 [21]

Wind turbine class	I	II	III	S
Annual mean wind speed at hub height (m/s)	<10	<8.5	<7.5	User defined
V_{ref} 50-year extreme 10-min wind speed (m/s)	<50	<42.5	<37.5	
50-year extreme 3-sec gust (m/s)	<70	<59.5	<52.5	

Table 22 Metocean conditions for structural feasibility – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to metocean conditions	Rationale with respect to metocean conditions for structural feasibility
RED	$H_{s_50yr} > 16$m and / or $V_{ref} > 50$ m/s	H_{s_50yr} consistent with Exposed site conditions and / or V_{ref} exceeds Wind turbine class I reference.
AMBER	$13\text{m} < H_{s_50yr} < 16$m and / or $42.5\text{m/s} < V_{ref} < 50$m/s	H_{s_50yr} consistent with Moderate site conditions and / or V_{ref} below Wind turbine class I reference but above class II reference.
GREEN	$H_{s_50yr} < 13$m $V_{ref} < 42.5$m/s	H_{s_50yr} consistent with Benign site conditions and V_{ref} below Wind turbine class II reference.

The resulting RAG map based on data from [18] is shown in Figure 13.

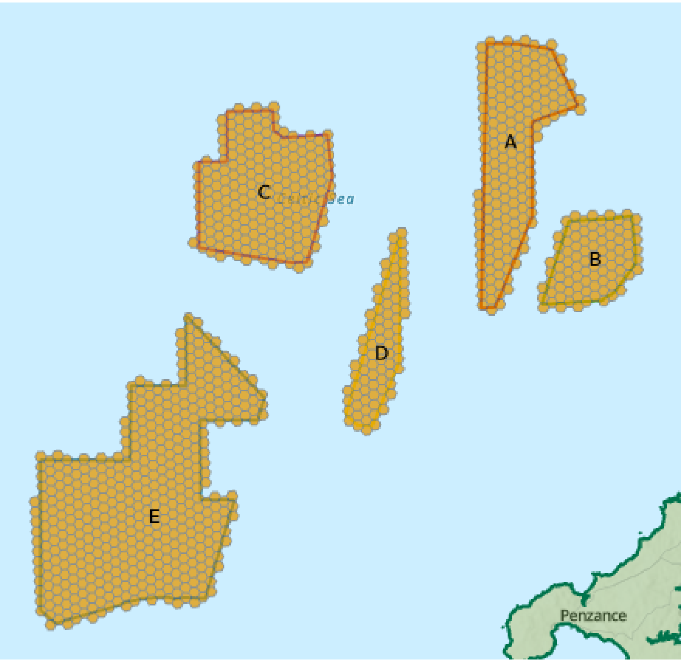


Figure 13 Metocean conditions for structural feasibility – RAG risk rating by hex-cell

Table 23 Metocean conditions for structural feasibility – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

5.3.7 Presence of shallow gas

The BGS provided two data sets in relation to shallow gas across the UKCS: areas where gas blanking has been identified and areas where there is a potential for, or confirmed presence of, pockmarks ([11], [12]).

The presence of shallow gas has the potential to cause issues with all anchor types during installation and operation. Sites of active seepage should be avoided for gravity anchors, pile anchors and suctions caissons due to the negative effects of fluid seepage and pore pressure accumulation on the in-place capacity.

Where methane seepage has occurred, this may result in the formation of carbonate concretions within material that is usually very soft. This may increase the risk of anchor pile refusal during installation and reduce the embedment depth and hence holding capacity of drag anchors.

Pockmarks from shallow gas expulsion will create an uneven seabed which may influence the length of mooring required (particularly for catenary and semi-taut mooring systems) and result in unsuitable seabed slopes for the installation of suction caissons and gravity anchors. The BGS factor map distinguishes large pockmarks with vertical relief higher than 10m as likely to be sites of active seepage [1].

The absence of physical indications of shallow gas does not necessarily mean it is not present within the sediments. The ability to successfully identify shallow gas will depend on the nature and thickness of sediments as well as the type of acoustic system used during geophysical surveys. Significant areas of gas accumulation could be unmapped due to the wide spacing between seismic lines [1].

The above considerations were used to assign a RAG rating to individual hex-cells based on criteria and rationale summarised in Table 24.

Table 24 Presence of shallow gas – RAG criteria and rationale by hex-cell

Risk rating	Criteria with respect to gas blanking and pockmarks	Rationale with respect to presence of shallow gas
RED	Large pockmarks.	Indicative of sites of active seepage, likely unsuitable for all anchor types.
AMBER	Pockmarks identified as present or with potential presence or shallow gas potential registered in 1 or 2 datasets.	Gas blanking identified, spatial extents require further investigation. Pockmarks may be present, indicative of active or historic seepage. Pockmarks may cause uneven seabed conditions that may be unsuitable for certain anchor types.
GREEN	Low likelihood of pockmarks and no shallow gas potential registered.	Lowest risks areas with respect to the potential for active seepage and uneven seabed associated with pockmarks.

The resulting RAG map based on data in [11] and [12] is shown in Figure 14.

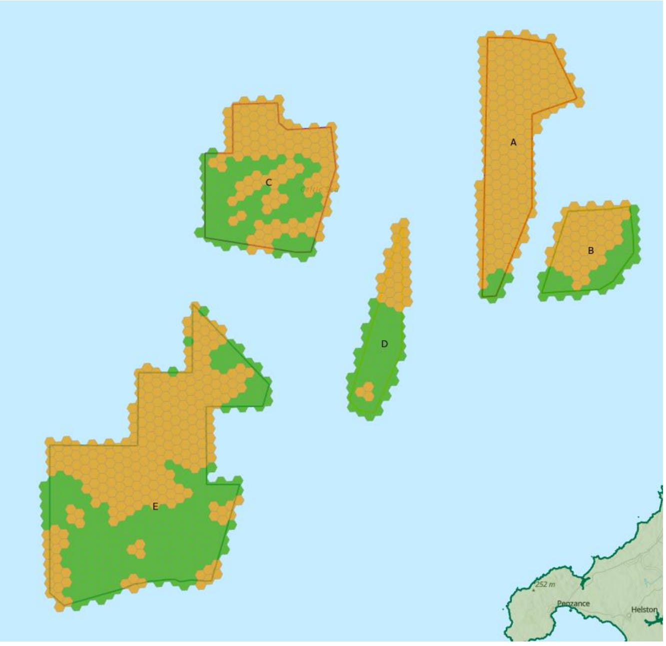


Figure 14 Presence of shallow gas – RAG risk rating by hex-cell

Table 25 Presence of shallow gas – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

5.4 Combined anchor risk summary

The majority of the above risks are not considered strongly interrelated, therefore generally the presence of one does not influence or affect any of the others. The exception to this is the combination of:

- *Depth to bedrock.*
- *Strength of bedrock for anchor installation.*
- *Metocean conditions for structural feasibility*.

These three risks are considered additive as both *depth to bedrock* and *strength of bedrock for anchor installation* affect the capacity of the anchorage system and *metocean conditions for structural feasibility* affects the demand on the anchorage system.

To combine these three risks a numeric value was assigned to the Red (1.0), Amber (0.5) and Green (0.0) categories. The combined anchor risk was the numeric value of the lowest of the two capacity-related risks (*depth to bedrock* and *strength of bedrock for anchor installation*) summed with the numeric value of the demand related risk (*metocean conditions for structural feasibility).* The combined anchor risk was then categorised according to: Red ≥1.0, 1.0>Amber≥0.5 and Green <0.5.

The lower of the two capacity-related risks was taken because low risk in either *depth to bedrock* or *strength of bedrock for anchor installation* is considered an indication that a feasible anchor solution of suitable strength is available.

Note that the lowest of the *depth to bedrock* and *strength of bedrock for anchor installation* was selected based on the average risk rating for each of the RAoS and not based on an assessment of the individual hex-cells to give a high-level interpretation of the combined anchor risk, rather than a more complex analysis of the three risk categories which would not be appropriate for this study. In all RAoS, *strength of bedrock for anchor installation* was the lower risk and so this criterion has been used in combination with the *metocean conditions for structural feasibility* to derive the *combined anchor risk*.

The resulting RAG map is shown in Figure 15.

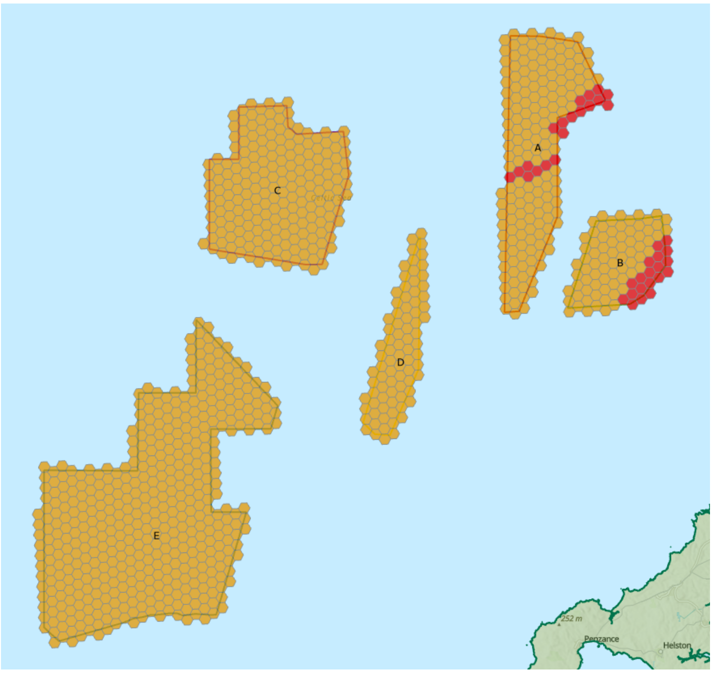


Figure 15 Combined anchor risk – RAG risk rating by hex-cell

Table 26 Combined anchor risk – average risk rating by RAoS

RAoS	Average risk rating
A	
B	
C	
D	
E	

Other risks may be interrelated, especially when considering specific FLOW support structures or technologies. However, where there is not a consistently strong interrelation, the risks were not incorporated into a combined risk. All risks were considered cumulatively as part of the maximum risk summary, as described below.

5.5 Maximum risk summary

The maximum risk for each hex-cell within the RAoS was examined by taking the highest risk rating across any of the eight risk categories (including the combined anchor risk). The average maximum risk rating was assigned to each RAoS by considering the average maximum risk rating across the hex cells within the RAoS.

The resulting RAG map is shown in Figure 16.

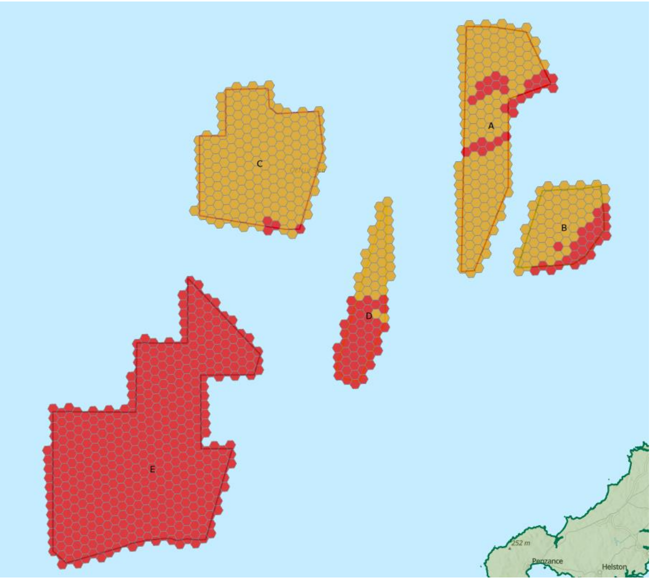


Figure 16 Maximum risk rating across all categories – RAG risk rating by hex-cell

Table 27 Average maximum risk rating by RAoS

RAoS	Average maximum risk rating
A	
B	
C	
D	
E	

5.6 Risk summary by RAoS

The key engineering risks identified across the RAoS and discussed in sections 5.3, 5.4, and 5.5 are summarised below.

Table 28 Summary of key engineering risks and maximum risk average rating across each RAoS

RAoS	Seabed depth	Depth to bedrock	Strength of bedrock for anchor installation	Wave loading for installation	Wave loading for O&M	Metocean conditions for structural feasibility	Presence of shallow gas	Combined anchor risk	Average maximum risk
A									
B									
C									
D									
E									

6. LCOE modelling

6.1 SCALE model methodology and approach

Arup's proprietary offshore wind deployment and LCOE modelling solution, SCALE, was used to provide LCOE output at the granularity of the 2.5km-diameter hexagonal grid across the five RAoS.

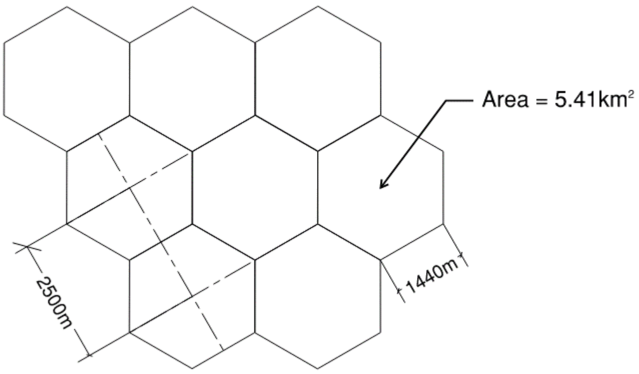


Figure 17 Hexagon grid dimensions

Alongside overall LCOE (£/MWh), the outputs of SCALE include:

- Annual estimated energy production (MWh).
- DEVEX (£).
- CAPEX (£).
- OPEX (£).
- DECEX (£).

For the purposes of this assessment, TCE provided values for total OPEX costs, transmission CAPEX costs, and availability informing annual estimated energy production which superseded the SCALE calculated values.

The SCALE modelling for this assessment was based on a 1.5GW wind farm operational in 2035 with a 20MW WTG and wind farm density of 6MW/km^2, at 2020 rates. Cost rate sources included TCE, Arup internal database, Offshore Renewable Energy Catapult Floating Offshore Wind Centre of Excellence, and publicly available sources. Cost rates utilised in SCALE for this assessment were broadly consistent with the cost rates used for the Future Offshore Wind Scenarios project also carried out by Arup for The Crown Estate, Crown Estate Scotland and BEIS in 2022 [24], with values updated for specific floating wind technologies as appropriate and where refined data was available.

The SCALE model generated values for the LCOE of offshore wind in all hex-cells, considering the floating foundations defined in Section 4 and site parameters defined by those associated with each hex-cell.

Technical and commercial assumptions (such as price per wind turbine and number of days installation required per foundation) were determined based on turbine rating and site parameters.

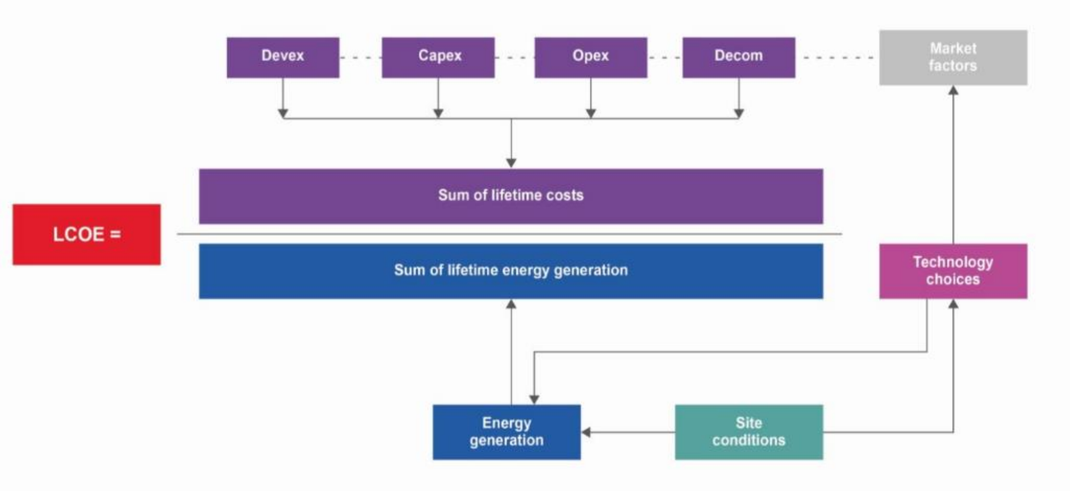


Figure 18 Components of an LCOE calculation

There are seven site specific geospatial inputs that were required to be defined for the LCOE calculation as listed in Table 29. Other input assumptions are outlined in the below the table. There are a number of user defined inputs for SCALE which were agreed with TCE as part of this assessment.

Table 29 Geospatial inputs required for LCOE calculation

Category	Dataset examples
Physical	Bathymetry.
	Geology.
Metocean data	Wind speed.
	Significant wave height 1:50yr return period.
	Annual mean significant wave height.
Onshore infrastructure	Distance to ports.
	Distance to onshore substations.

6.2 Cost estimates and assumptions

The annual energy production, all costs and subsequent LCOE estimates in the modelling provide a relative comparison for this strategic and high-level assessment. They should not be relied upon for other purposes.

The costs were based on a spend profile that follows a typical UK offshore wind farm project timeline shown in Figure 19.

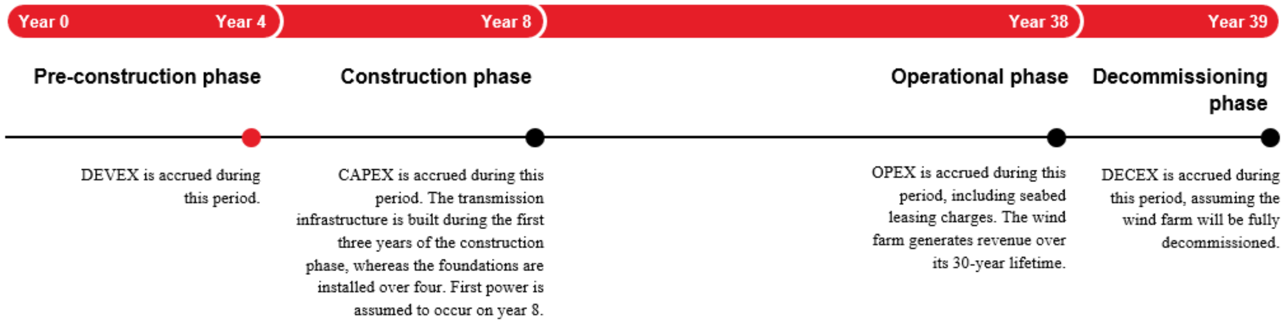


Figure 19 Assumed project timeline

The relative LCOE calculations were based on the lowest-cost solution for each location, considering floating foundations as described in Section 4:

- Steel semi-submersibles,
- Steel TLPs, and
- Concrete barges

Alongside associated mooring and anchor arrangements. The technology choice within SCALE was determined by technical viability based on site conditions. The model selects the lowest-cost solution where more than one foundation (and mooring and anchor) type is viable.

The cost estimates accounted for the following:

DEVEX

DEVEX costs covered development costs including activities such as consenting, engineering, certification, and surveys. For the purposes of this study, the same costs were assumed for all developments.

CAPEX

CAPEX costs included fabrication, transport and installation of the turbines, foundations, and wind farm transmission infrastructure (array cables, substation and export cables). The foundations were based on concept-level designs that varied depending on site specific conditions such as water depth, seabed composition and metocean conditions, as well as the WTG size. WTG size was assumed to be 20MW.

Installation was based on selected ports identified as suitable for offshore wind construction and included weather downtime. Ports considered suitable for construction bases and O&M around the Celtic Sea included Port of Milford Haven, Port Talbot and Falmouth Docks for both functions. For the purposes of this analysis, only Port of Milford Haven and Falmouth Docks were considered within the model.

Transmission infrastructure costs were based on the distance between the wind farm and the nearest primary onshore substation. For this study Pembroke and Alverdiscot primary substations were assumed. For wind farms within 100km of these substations, a High Voltage Alternating Current (HVAC) transmission system, costs and electrical cable losses were assumed. For wind farms further away, High Voltage Direct Current (HVDC) was assumed.

Costs related to insurance, contingency and project management were also included.

OPEX

OPEX costs included maintenance associated with major, minor, and preventive repairs and are estimated using the nearest suitable UK maintenance port considered in the model. The model selected either a Crew Transfer Vessel (CTV) or Service Operation Vessel (SOV) maintenance strategy, depending on the site specific metocean conditions and distance to port. In this assessment, the preferred maintenance strategy for all sites utilised SOVs due to the metocean conditions and distance from shore of the sites.

Metocean conditions for installation and operations were categorised based on annual mean significant wave height, informing operations approach and weather downtime, as follows (these are consistent with the RAG risk assessment categories for installation and O&M):

- Mild: <1.35m (Green).
- Benign: < 2m (Green).
- Moderate: <2.5m (Amber).
- Harsh: >2.5m (Red).

The Transmission Network Use of System (TNUoS) charge depends on where in the country a generator is connecting to the grid, designed to reflect the cost to the transmission system of generators connecting in different locations. For this assessment an average cost across grid charge zones 20 and 27 was used. The SCALE model assumed the “wider-tariff” component of National Grid’s 2023 published five-year forecast [23] and then kept the TNUoS constant for each grid charge zone.

Costs also included insurance.

DECEX

DECEX costs assumed full decommissioning of the wind farm cluster after 30 years of operation, involving the removal of foundations, turbines, and substations.

Annual Energy Production

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

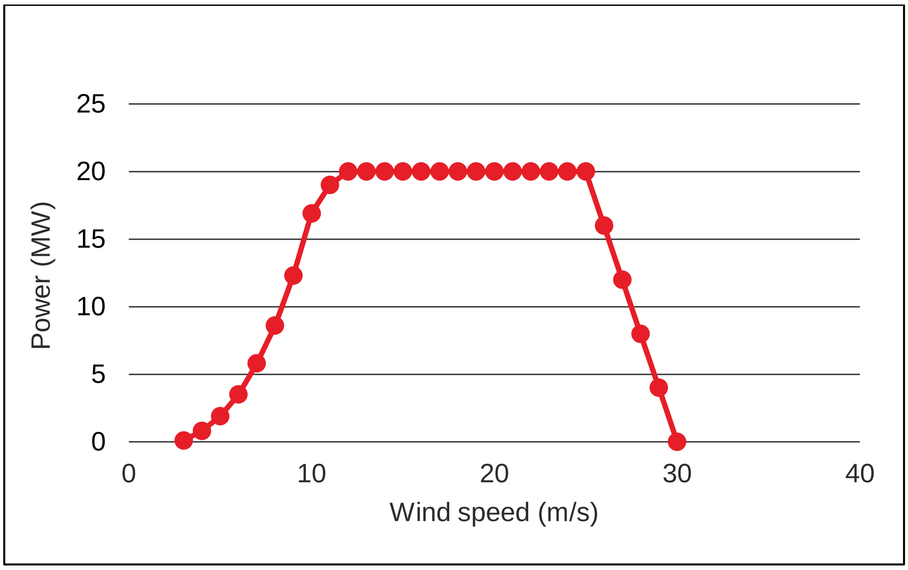


Figure 20 20MW WTG Power Curve

Losses were assumed as per Table 30 in agreement with TCE.

Table 30 Losses applied within the model to the estimated AEP

Loss factor	Percentage loss
Array interactions (wake & blockage).	7.00%
Transmission cable losses.	Calculated per hex-cell.
All other losses (inc. inter-array cables, WTG, OFTO & grid, generic power curve adjustment, floating wind power curve adjustment).	4.4%

Cost of capital

This study considered cost of capital as the weighted average cost of capital (WACC) applicable to financing UK offshore wind projects, taken as 6% for floating projects. All values modelled and quoted for are in real terms, consistent with the basis of the cost estimations. A simple financing structure was assumed, where the key components are cost of equity, cost of debt and the mix of equity and debt used to finance a project.

Future cost projections

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

Within the SCALE model for this assessment learning rates were applied to floating offshore wind projects from the point in time where the global floating offshore wind installed capacity is assumed to have reached 2GW. The assumed global floating offshore wind capacity profile, applied in this assessment, was based on industry views of likely globally installed capacity by 2032 (the assumed year of foundation supply), from, for example, BloombergNEF [25].

It was assumed that there will be two doublings of capacity by 2035 (from 2GW to 4GW to 8GW). e.g. If the cost rate reduction per doubling of global capacity for floating sub-structures is 15%, then the estimated cost factor in 2035 is equal to $(100\%-15\%)^2$ = 72.3% of the 2020 base rate.

Actual learning rates likely to be achieved are subject to high levels of uncertainty impacted by the deployment profile of offshore wind and a range of wider market factors.

6.3 SCALE model limitations and considerations

SCALE carries out temporal and spatial modelling of the relative Levelised Cost of Energy (LCOE) of offshore wind across specified model boundaries for a given period of time.

The LCOE module generates values for the LCOE of offshore wind considering both fixed and floating foundations (note only floating foundations have been considered for this assessment). The output is suitable for relative assessment of LCOE across different geospatial locations within the model boundary.

An overview of some of the key limitations associated with the assessment is presented below.

- Deployment was based on a 1.5GW default wind farm.
- The model did not take into consideration any onshore transmission network limitations, such as the maximum grid capacity of onshore substations.
- Port and supply chain capacity were excluded from the scope of the model. It was assumed that these will be developed at such a scale as to not provide a limitation to the deployment of FLOW in the Celtic Sea. At a further stage of development, when more detailed understanding of future port capability and project specific preferences are known, different input assumptions may impact on the conclusions.
- The LCOE model was based on radial connections to shore and did not consider potential offshore transmission hubs that could lead to benefits at a whole system scale and could influence the most favourable locations for offshore wind deployment.
- The LCOE model utilised cost rate assumptions (2020 pre-tax real term) which are subject to change in line with factors such as (but not limited to) market conditions and cost reductions over time, and the commercial, regulatory and legislative environment.
- The LCOE model calculated an estimate for Annual Energy Production (AEP) based on project input parameters, built in calculations and location-specific wind speed data. This estimate is subject to change in line with changes to factors such as (but not limited to) variation in site specific conditions and wind speed, alongside project specific layout and wind yield optimisation.
- Foundation designs were based on concept-level designs using Arup's offshore wind foundation design suite. Concept designs do not include allowance for seabed mobility, detailed fatigue or seismic design. The floating technology type results were based on the agreed input assumptions and do not represent recommendations for offshore wind floating technology selection at this stage.
- Overall, there are inherent uncertainties with LCOE analysis at this very early stage of development, when specific project locations and decisions are yet to be determined, uncertainty analysis was not carried out and the outputs from the analysis for this assessment are subject to change. Where actual values are included, this is for information only, these should be read in the context of this assessment, input assumptions and analysis approach, are subject to uncertainty and should not be relied upon.

6.4 LCOE outputs

6.4.1 Overview of LCOE output by RAoS

The outputs from the LCOE analysis are normalised so that the hex-cell with the lowest LCOE has a value of zero and the hex-cell with the highest LCOE has a value of one. The presentation of normalised values allows for a relative assessment of LCOE across the RAoS. The results of the LCOE calculations for each RAoS are summarised in Figure 21. The RAoS with lowest LCOE were areas A and B, followed by C and D, with E having the highest LCOE.

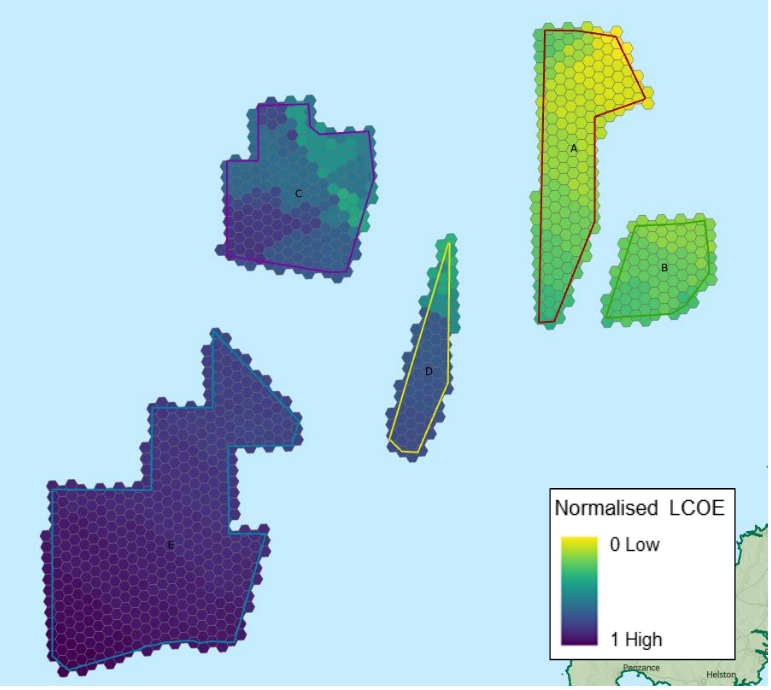


Figure 21 Summary of LCOE across each RAoS

Note the normalised LCOE values provided are suitable for relative assessment of the RAoS as part of this assessment only and should not be relied upon outside the purposes of this assessment.

6.4.2 FLOW technology analysis

The lowest cost floating technology type selected across the whole model was the steel TLP, taking into account the input assumptions within the model at the time of analysis. Note that advances in technology readiness level, or site specific considerations will play into the final technology selection for any given site.

Steel TLP CAPEX was driven by the lower CAPEX cost associated with the floating components when compared with the alternative technologies. Note that these results are limited to the water depths found in the five RAoS, between 70m to 120m, and a different trend would be expected in deeper waters.

In addition, for this SCALE model analysis, the OPEX model was kept the same for all technologies, assuming that sub-structures and turbines can be towed back to the O&M port as a whole unit. It is unlikely that this will be the case for TLP foundations, as the turbines would need to be dismantled offshore, increasing OPEX and potentially making it more expensive than a concrete barge or semi-submersible solution, for example.

The contribution of anchor supply and installation made a relatively limited contribution to CAPEX, representing approximately 7%, on average, of the total CAPEX across all foundation types. This translated to a contribution to LCOE of less than 3%, on average. In RAoS C, which displayed the widest variability in type of quaternary deposit and depth to bedrock, increases in the LCOE could be observed linked the ground conditions due to changes in the pile size and installation times.

In terms of suitability, all five FLOW technology combinations described in Section 4 (combinations of support structure and moorings) could be deployed in the five RAoS.

The feasibility of anchor type depends primarily on two factors in the LCOE calculation: depth to bedrock, and quaternary deposit type. The following observations are made:

- Drilled piles would be suitable in areas with shallow (<5m) and intermediate (<20m) bedrock depths. This covers all areas, other than the majority of RAoS C and a small corner of RAoS A where deeper bedrock has been identified.
- Gravity anchors would be feasible in theory across most of the RAoS due to the presence of shallow bedrock overlaid by normal to hard quaternary deposits. However, the CAPEX of drilled piles in the same conditions is found to be significantly lower.
- Drag-embedded and driven pile anchors are not considered feasible in a large part of RAoS A, B or E, half of D and a small part of C, which have a bedrock depth of less than 20m.
- Suction caissons are not feasible in the majority of RAoS E and the lower half of RAoS D, where bedrock depth is less than 5m. In the intermediate bedrock depth range, drilled piles are identified to outperform suction caissons with respect to CAPEX.

7. Project Development Area assessments

The following section, summarising Phase 2 of the project, provides a summary of the key engineering risks associated with each PDA.

The final PDAs as determined by TCE are shown below in Figure 22, the final decision on PDA locations was determined by TCE taking into account output from Phase 1 of this assessment alongside other supporting work and decision making factors not included within this report.

The PDAs are located across RAoS A and B, which are two of the lower-risk and lower-cost RAoS based on key engineering risk identification and high-level LCOE assessment summarised in Sections 5 and 6 of this report.

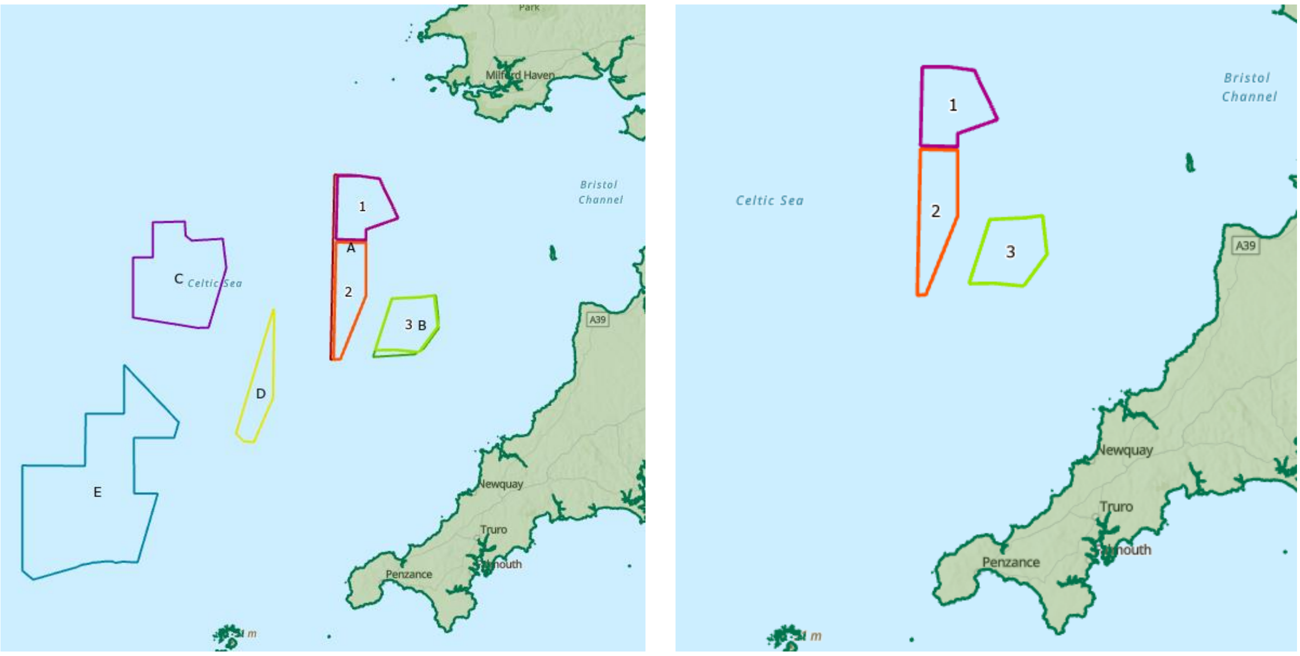


Figure 22 PDA areas 1-3 (shown within the RAoS on left)

For each of the three PDAs, a risk assessment summary is provided, this summary includes a narrative of the risk ratings and potential implications of these for the deployment of FLOW within each PDA. Two tables are provided for each PDA:

- The first table provides the risk assessment summary for the PDA. This provides the average risk rating for each of the seven key engineering risks based on the criteria for each risk outlined in Section 5.3, as well as the combined anchor risk and the average maximum risk rating for the PDA.
- The second table provides the RAG map for each of the seven key engineering risks alongside the map of the underlying data for each PDA. Larger maps of the underlying data across all three PDAs are provided in Appendix B.

7.1 PDA 1

The engineering risks and their applicability for PDA 1 are summarised below. The average ratings across the hex-cells for each of the risk categories across PDA 1 are shown in Table 31, with detail of the variation of risk across the PDA, along with the underlying data, provided in Table 32. The qualitative criteria relating to RAoS A (of which PDA 1 lies within) is detailed in Section 5.3 of this report.

- Risk associated with *Seabed depth* was assessed as AMBER.

  This represents a depth range that is feasible for semi-submersible, monohull / barge and TLP support structures. The depth range was considered too shallow for a conventional spar, typically requiring depths greater than 120m.

- For the risks associated with mooring anchors: *depth to bedrock* was assessed as AMBER and *strength of bedrock for anchor installation* was assessed as GREEN.

  Suction caissons and drag anchors, the lowest cost and simplest anchor types, may only start to be feasible at the upper end of the bedrock depth range covering most of PDA 1. Most of PDA 1 is in the 5 to 20m *depth to bedrock* range (see Table 32) and these anchor types only start to become feasible at depths of around 20m or greater. The bedrock type underlying the majority of PDA 1 is likely to be chalk based on the available data. Depending on the strength of the chalk and the potential presence of flint bands, installation of piled anchors into the rock may be by driving or drilling. Chalk is susceptible to strength degradation due to both installation processes and cyclic loading during operation which may lead to larger anchor sizes (or a greater number of anchors), specifically for anchor piles under tension loading (i.e. for TLPs), when compared to other rock types with a comparable in-situ strength.

  PDA 1 exhibits a complex structural geology, with BGS mapping in the area including both faulting at depth and the presence of salt piercements [6]. This setting can lead to lateral and vertical variation in bedrock strength and composition in the vicinity of these features. Site specific geophysical investigations and follow-on geotechnical field campaigns should enable the complexity of the structural geology to be better understood, specifically at depths relevant to anchor installation.

- Risks associated with *wave loading for installation* and *wave loading for O&M* were assessed as AMBER.

  Mean sea state presents weather windowing challenges for certain activities, e.g. use of floating cranes to install WTGs or coupling or de-coupling support structures from their mooring systems for installation or tow back to port for major maintenance.

- Risk associated with *metocean conditions for structural feasibility* was assessed as AMBER.

  The support structure and mooring configuration will need to withstand moderate extreme wind and wave loading.

- Risk associated with the *presence of shallow gas* was assessed as AMBER.

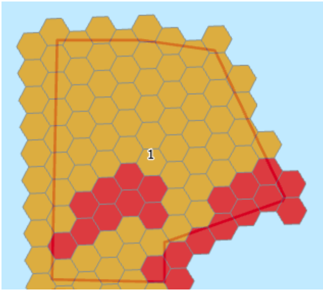
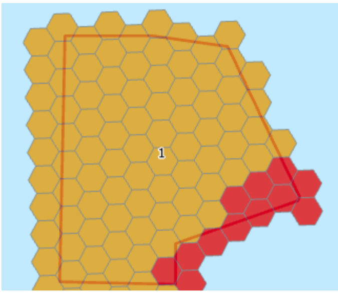
  Gas blanking was not identified in the datasets reviewed within PDA 1. Pockmarks are generally shown to have a 'potential presence' across all of PDA 1. While the presence of pockmarks has not been verified in this area, the occurrence of pockmarks is considered possible based on the BGS knowledge of seabed sediment and its implication for pockmark development. If further investigations identify the presence of uneven seabed slopes, active fluid flow or local concretions in the seabed sediment this may restrict the choice of anchor.

- PDA 1 is crossed by four telecommunication cable routes, cable owners should be consulted during development to ensure suitable buffers and management arrangements are agreed.

- UXOs present a potential risk to the development of FLOW in the Celtic Sea, principally due to the UXO residue from both World War One (WWI), World War Two (WWII), and modern military training and practice exercises. A full and detailed UXO Risk Assessment is required to assess the risk to development of FLOW in PDA 1, considering in detail the findings from the UXO hazard assessment and the environmental and ground conditions across the sites.

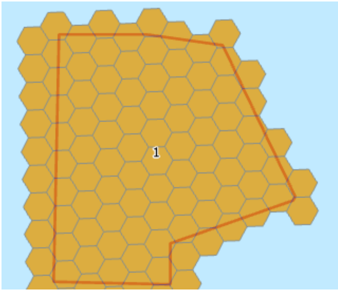
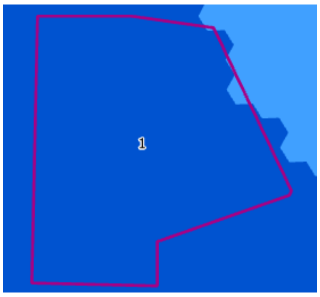
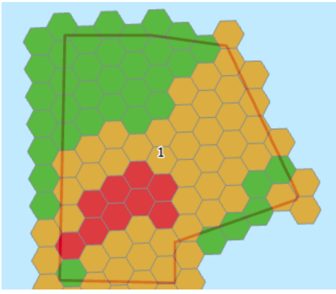
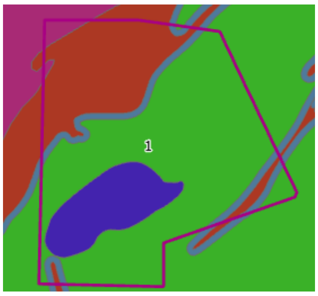
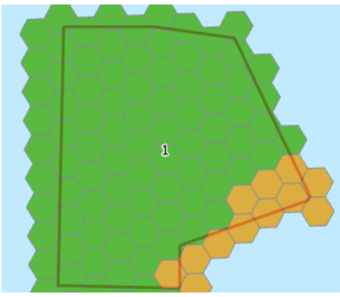
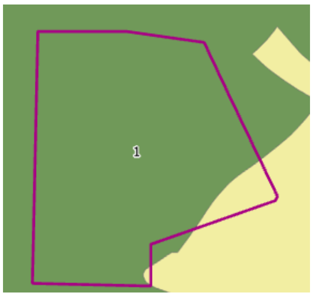
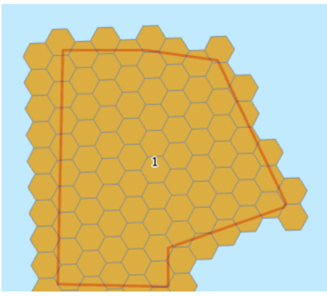
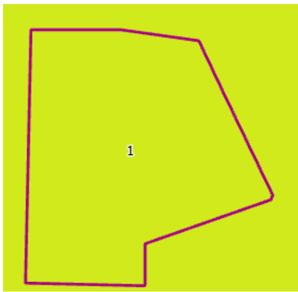
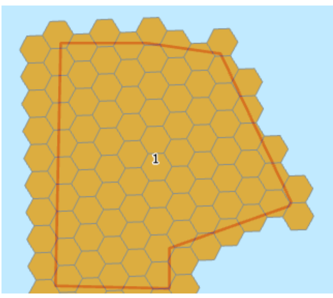
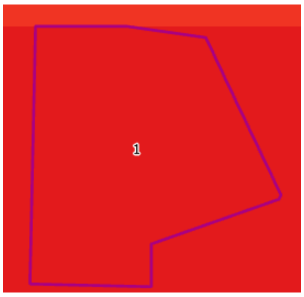
The average rating for each of the risk categories across PDA 1 are shown in Table 31. Definitions of the risk factors and risk rating criteria are as per Section 5.3.

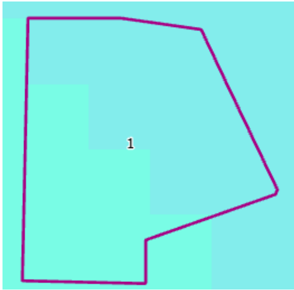
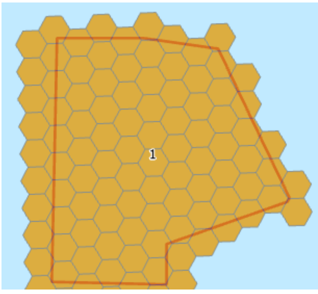
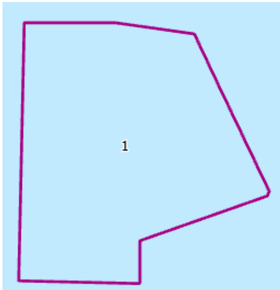
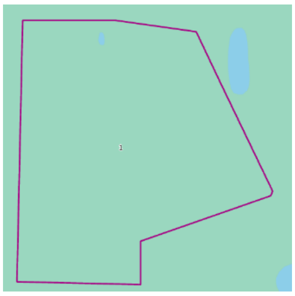
Table 31 Risk assessment summary for PDA 1

Risk factor	Criteria for average risk rating	Risk summary	Average risk rating
Maximum risk.	n/a	 The highest risk rating across any of the risk categories.	
Seabed depth.	50m – 120m.	Depth range where semi-submersible, monohull / barge and TLP support structures (but not all types of floating technology) are considered feasible.	
Depth to bedrock.	5m – 20m.	Not all anchor types are likely to be feasible. Suction caissons and drag anchors, the lowest cost and simplest anchor solutions, may only start to become feasible at upper end of depth range (20m).	
Strength of bedrock for anchor installation.	Weak rock types: Chalk. Medium strength rock type: Mesozoic Interbedded.	May be feasible to install piles by driving or DDD techniques. If installation is by drilling, higher relative progress rate.	
Wave loading for installation / O&M.	2m – 2.5m.	Moderate mean sea state. Weather windowing for some more sensitive installation activities will be challenging.	
Metocean conditions for structural feasibility.	13m < H_{s_50yr} < 16m and 42.5m/s < V_{ref} < 50m/s.	H_{s_50yr} consistent with moderate site conditions and or V_{ref} below wind turbine class I reference but above class II reference.	
Presence of shallow gas.	Pockmarks identified as potentially present.	Pockmarks may be present, indicative of active or historic seepage. Pockmarks may cause uneven seabed conditions that may be unsuitable for certain anchor types.	
Combined anchor risk.	n/a	 The combination of *depth to bedrock* and *strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*. These three risks are considered additive as both *depth to bedrock* and *strength of bedrock for anchor installation* affect the capacity of the anchorage system and *metocean conditions for structural feasibility* affects the demand on the anchorage system.	

The RAG maps and underlying data for PDA 1 are shown in Table 32, which provides more detail on the physical and metocean conditions that fed into the risk ratings for PDA 1. Larger maps of the underlying data can be found in Appendix B.

Table 32 RAG maps and underlying data for PDA 1

Risk factor	RAG map	Underlying data (see Appendix B for larger maps)
Seabed depth.		 Range in PDA: 68m to 84m
Depth to bedrock.		 Range in PDA: 0m to >50m
Strength of bedrock for anchor installation.		
Wave loading for installation / O&M.		 Range in PDA: 2.1m to 2.2m
Metocean conditions for structural feasibility.		 Range in PDA: 13m to 14m

		 Range in PDA: 46.8m/s to 47.5m/s
Presence of shallow gas.		 

7.2 PDA 2

The engineering risks and their applicability for PDA 2 are summarised below. The average ratings across the hex-cells, for each of the risk categories across PDA 2 are shown in Table 33 with detail of the variation of risk across the PDA, along with the underlying data, provided in Table 34. Reference should also be made to the qualitative discussions relating to RAoS A (of which PDA 2 lies within) in Section 5.3 of this report.

- Risk associated with *seabed depth* was assessed as AMBER.

  This represents a depth range that is feasible for semi-submersible, monohull / barge and TLP support structures. The depth range was considered too shallow for a conventional spar, typically requiring depths greater than 120m.

- The risks associated with mooring anchors: *depth to bedrock* was assessed as AMBER and *strength of bedrock for anchor installation* was assessed as GREEN.

  As for PDA 1, suction caissons and drag anchors may only start to be feasible at the upper end of the bedrock depth range covering most of PDA 2. Most of PDA 2 is in the 5 to 20m *depth to bedrock* range (see Table 34) and these anchor types only start to become feasible at depths of around 20m or greater. The underlying data for *depth to bedrock* included in Table 34 shows the presence of a series of southwest to northeast trending "incisions" into the bedrock in PDA 2, where the local thickness of quaternary deposits is in excess of 50m. This may result in the need for different anchor types within the PDA to suit the variable ground conditions.

  The northern area of PDA 2 is largely underlain by chalk. Depending on the strength of the chalk and the potential presence of flint bands, installation of piled anchors into the rock may be by driving or drilling. Chalk is susceptible to strength degradation due to both installation processes and cyclic loading during operation which may lead to larger anchor sizes (or a greater number of anchors), specifically for anchor piles under tension loading (i.e. for TLPs), when compared to other rock types with a comparable in-situ strength.

  A small band of Mesozoic interbedded bedrock is shown to run roughly east to west, this is expected to be higher strength than the other bedrock types shown which will result in more complex conditions for installation but likely higher anchor capacities. The southern area of PDA 2 is largely underlain by Tertiary interbedded bedrock, expected to be primarily sandstones and mudstones. Anchor capacities, specifically for anchor piles loaded in tension for TLPs, are anticipated to be higher in these rock types than in the chalk to the north. Installation of anchor piles in this material may be achievable by driving or drive-drill-drive techniques. Where drilling is required, progress rates should be higher than in other more competent rock types.

  PDA 2 exhibits a complex structural geology, with BGS mapping in the area showing folding of the bedrock and faulting at rockhead and at greater depths [6]. The risks associated with this setting and the requirement for detailed geophysical and geotechnical investigations as outlined for PDA 1 also apply here. This setting can lead to lateral and vertical variation in bedrock strength and composition in the vicinity of these features. Site specific geophysical investigations and follow-on geotechnical field campaigns should enable the complexity of the structural geology to be better understood, specifically at depths relevant to anchor installation.

- Risks associated with *wave loading for installation* and *wave loading for O&M* were assessed as AMBER.

  Mean sea state presents weather windowing challenges for certain activities, e.g. use of floating cranes to install WTGs or coupling or de-coupling support structures from their mooring systems for installation or tow back to port for major maintenance.

- Risk associated with *metocean conditions for structural feasibility* was assessed as AMBER.

  The support structure and mooring configuration will need to withstand moderate extreme wind and wave loading.

- Risk associated with the *presence of shallow gas* was assessed as AMBER.

  Gas blanking was not identified in the datasets reviewed within PDA 2. Pockmarks are generally shown to have a 'potential presence' across all of PDA 2. While the presence of pockmarks has not been verified in this area, the occurrence of pockmarks is considered possible based on the BGS knowledge of seabed sediment and its implication for pockmark development. If further investigations identify the presence of uneven seabed slopes, active fluid flow or local concretions in the seabed sediment this may restrict the choice of anchor.

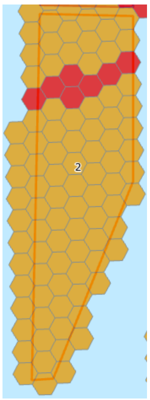
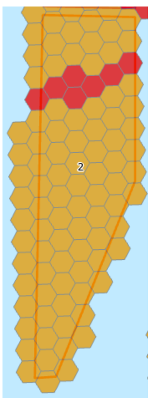
- PDA 2 is crossed by two telecommunication cable routes, cable owners should be consulted during development to ensure suitable buffers and management arrangements are agreed.

  An up to 500m buffer is proposed around the red-risk cable route, which should be considered in future development stages.

- UXOs present a potential risk to the development of FLOW in the Celtic Sea, principally due to the UXO residue from both World War One (WWI), World War Two (WWII), and modern military training and practice exercises. A full and detailed UXO Risk Assessment is required to assess the risk to development of FLOW in PDA 2, considering in detail the findings from the UXO hazard assessment and the environmental and ground conditions across the sites.

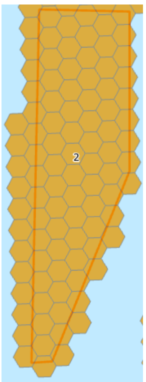
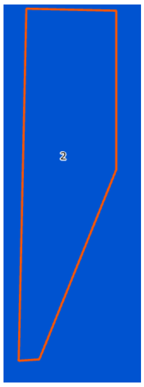
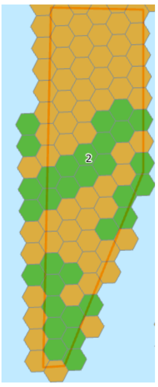
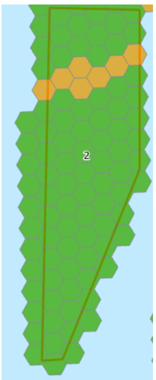
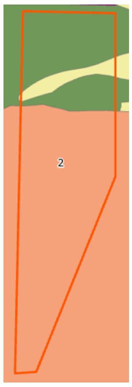
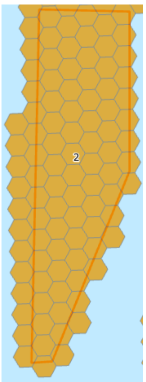
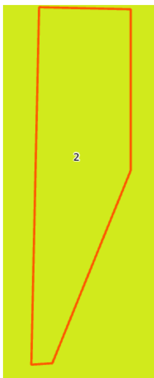
The average rating for each of the risk categories across PDA 2 are shown in Table 33. Definitions of the risk factors and risk rating criteria are as per Section 5.3.

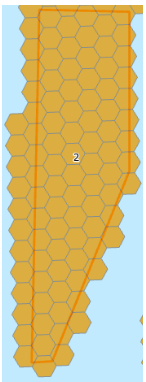
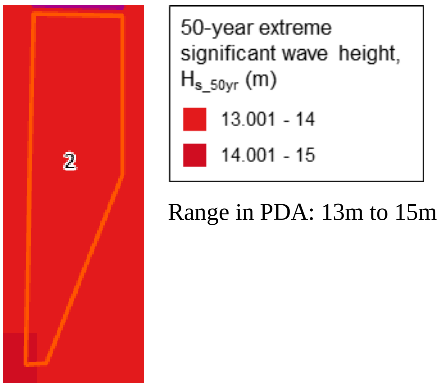
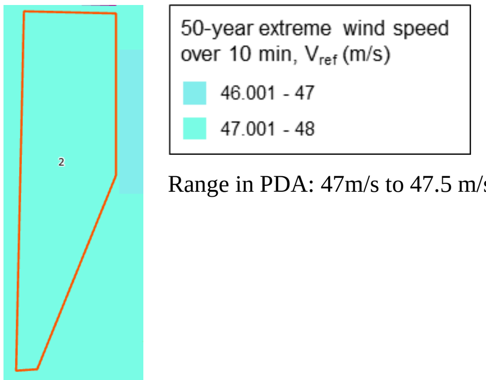
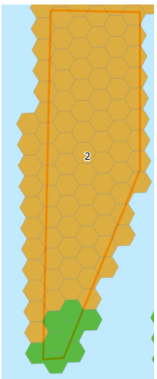
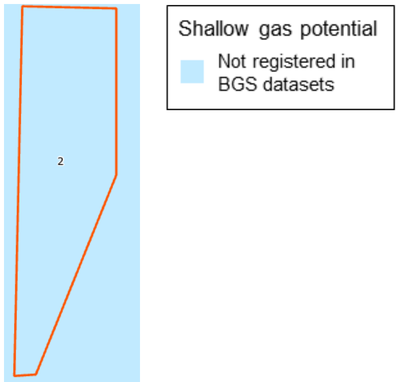
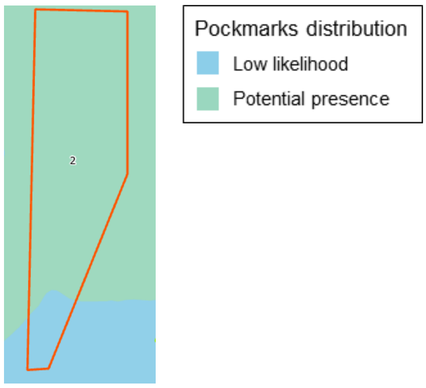
Table 33 Risk assessment summary for PDA 2

Risk factor	Criteria for average risk rating	Risk summary	Average risk rating
Maximum risk.	n/a	 The highest risk rating across any of the risk categories.	
Seabed depth.	50m – 120m.	Depth range where semi-submersible, monohull / barge and TLP support structures (but not all types of floating technology) are considered feasible.	
Depth to bedrock.	5m-20m.	Not all anchor types are likely to be feasible. Suction caissons and drag anchors, the lowest cost and simplest anchor solutions, may only start to become feasible at upper end of depth range (20m). Local incisions in the bedrock corresponding to increased thickness of quaternary deposits may increase number of anchor solutions required within the PDA.	
Strength of bedrock for anchor installation.	Weak rock types: Chalk, Tertiary interbedded. Medium strength rock type: Mesozoic interbedded.	May be feasible to install piles by driving or DDD techniques in weak rock types. If installation is by drilling, higher relative progress rate.	
Wave loading for installation / O&M.	2m – 2.5m.	Moderate mean sea state. Weather windowing for some more sensitive installation activities will be challenging.	
Metocean conditions for structural feasibility.	$13m < H_{s\_50yr} < 16m$ and $42.5m/s < V_{ref} < 50m/s$.	H_{s_50yr} consistent with moderate site conditions and/ or V_{ref} below wind turbine class I reference but above class II reference.	
Presence of shallow gas.	Pockmarks identified as potentially present.	Pockmarks may be present, indicative of active or historic seepage. Pockmarks may cause uneven seabed conditions that may be unsuitable for certain anchor types.	
Combined anchor risk.	n/a	 The combination of *depth to bedrock* and *strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*. These three risks are considered additive as both *depth to bedrock* and *strength of bedrock for anchor installation* affect the capacity of the anchorage system and *metocean conditions for structural feasibility* affects the demand on the anchorage system.	

The RAG maps and underlying data for PDA 2 are shown in Table 34, which provides more detail on the physical and metocean conditions that fed into the risk ratings for PDA 2. Larger maps of the underlying data can be found in Appendix B.

Table 34 RAG maps and underlying data for PDA 2

Risk factor	RAG map	Underlying data (see Appendix B for larger maps)
Seabed depth.		 Range in PDA: 71m to 88m
Depth to bedrock.		 Range in PDA: 5m to >50m
Strength of bedrock for anchor installation.		
Wave loading for installation / O&M.		 Range in PDA: 2.2m to 2.3m

<table>
<tr>
<td>Metocean conditions for structural feasibility.</td>
<td></td>
<td>
Range in PDA: 13m to 15m

Range in PDA: 47m/s to 47.5 m/s</td>
</tr>
<tr>
<td>Presence of shallow gas.</td>
<td></td>
<td>
</td>
</tr>
</table>

7.3 PDA 3

The engineering risks and their applicability for PDA 3 are summarised below. The average ratings across the hex-cells, for each of the risk categories across PDA 3 are shown in Table 35 with detail of the variation of risk across the PDA, along with the underlying data, provided in Table 36. Reference should also be made to the qualitative discussions relating to RAoS B (which is very similar to the area of PDA 3) in Section 5.3 of this report.

- Risk associated with *seabed depth* was assessed as AMBER.

  This represents a depth range that is feasible for semi-submersible, monohull / barge and TLP support structures. The depth range was considered too shallow for a conventional spar, typically requiring depths greater than 120m.

- The risks associated with mooring anchors: *depth to bedrock* was assessed as AMBER and *strength of bedrock for anchor installation* was assessed as GREEN.

  Other than the southeastern corner of PDA 3, the variation in depth to bedrock is comparable to PDA 2, including the presence of southwest to northeast trending incisions in the bedrock. This may result in the need for different anchor types within the PDA to suit the variable ground conditions.

  The underlying bedrock is shown as Tertiary interbedded. This Tertiary interbedded bedrock is expected to be primarily sandstones and mudstones. Anchor capacities, specifically for anchor piles loaded in tension for TLPs, are anticipated to be higher in these rock types than in chalk identified in areas of PDA1 and PDA 2. Installation of anchor piles in this material may be achievable by driving or drive-drill-drive techniques. Where drilling is required, progress rates should be higher than in other more competent rock types. In contrast to PDA 1 and PDA2, chalk has not been identified in PDA 3. This is anticipated to be beneficial for the capacity of any tension piles for TLPs installed in bedrock across this PDA.

  The depth to bedrock is shown as less than 5m in the southeastern corner of PDA 3, restricting the choice of mooring anchors to piled or gravity anchor solutions in this area.

  Although on average the *strength to bedrock for anchor installation* was assessed as low risk, the underlying bedrock in this southeastern corner is identified as Palaeozoic sedimentary. Review of the regional geology indicates this rock is a continuation of the undivided Carboniferous and Devonian bedrocks encountered onshore in Southwest England [6]. This rock is older and expected to be higher strength than the bedrock encountered elsewhere in the PDAs, resulting in a more challenging environment (costly, slower progress rates) for drilled installation of anchor piles. Once installed, higher anchor capacities are anticipated in this material compared to the other bedrock types identified.

- Risks associated with *wave loading for installation* and *wave loading for O&M* were assessed as AMBER.

  Mean sea state presents weather windowing challenges for certain activities, e.g. use of floating cranes to install WTGs or coupling or de-coupling support structures from their mooring systems for installation or tow back to port for major maintenance.

- Risk associated with *metocean conditions for structural feasibility* was assessed as AMBER.

  The support structure and mooring configuration will need to withstand moderate extreme wind and wave loading.

- Risk associated with the *presence of shallow gas* was assessed as AMBER.

  Gas blanking was not identified in the datasets reviewed within PDA 3. A lower likelihood of pockmarks was identified along the eastern edge of PDA 3 compared to the other areas. While the presence of pockmarks has not been verified in this area, the occurrence of pockmarks is considered possible based on the BGS knowledge of seabed sediment and its implication for pockmark development. If further investigations identify the presence of uneven seabed slopes, active fluid flow or local concretions in the seabed sediment this may restrict the choice of anchor.

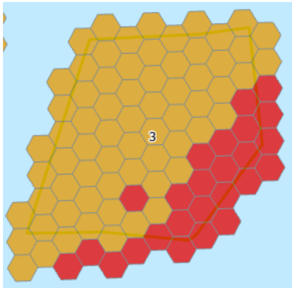
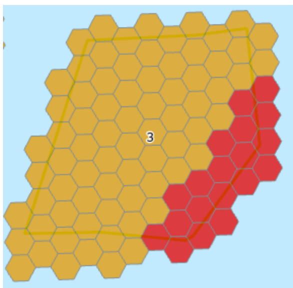
- PDA 3 is crossed by four telecommunication cable routes, cable owners should be consulted during development to ensure suitable buffers and management arrangements are agreed.

  An up to 500m buffer is proposed around the red-risk cable route, which should be considered in future development stages.

- UXO present a potential risk to the development of FLOW in the Celtic Sea, principally due to the UXO residue from both World War One (WWI), World War Two (WWII), and modern military training and practice exercises. A full and detailed UXO Risk Assessment is required to assess the risk to development of FLOW in PDA 1, considering in detail the findings from the UXO hazard assessment and the environmental and ground conditions across the sites.

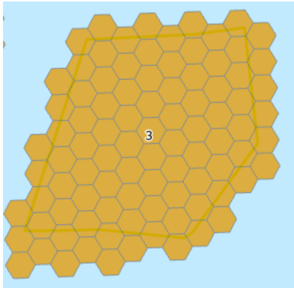
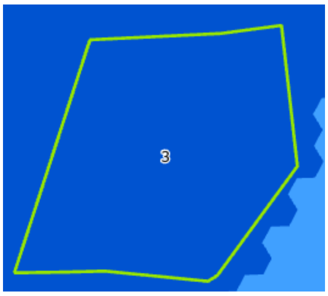
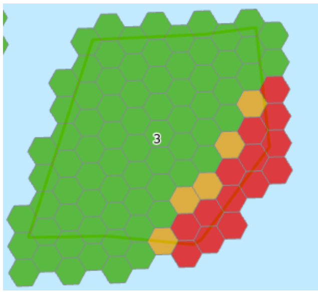
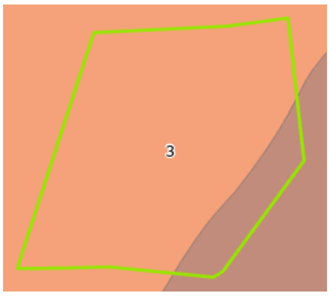
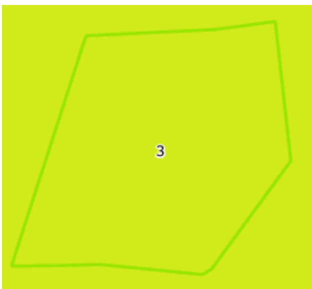
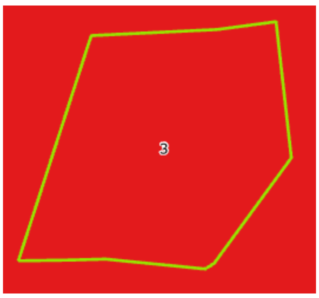
The average rating for each of the risk categories across PDA 3 are shown in Table 35. Definitions of the risk factors and risk rating criteria are as per Section 5.3.

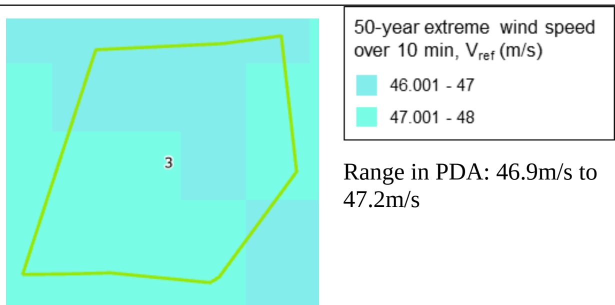
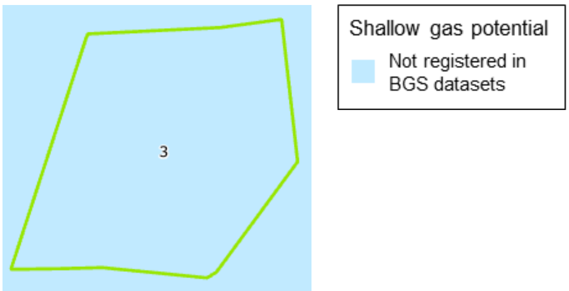
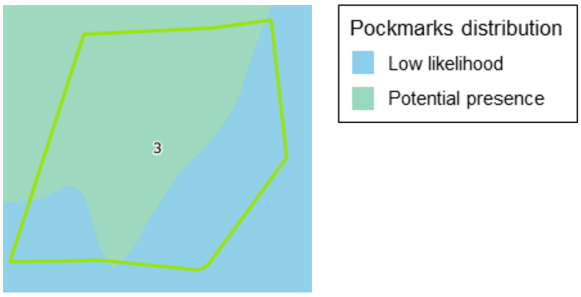
Table 35 Average risk rating for PDA 3

Risk factor	Criteria for average risk rating	Risk summary	Average risk rating
Maximum risk.	n/a	 The highest risk rating across any of the risk categories.	
Seabed depth.	50m – 120m.	Depth range where semi-submersible, monohull / barge and TLP support structures (but not all types of floating technology) are considered feasible.	
Depth to bedrock.	5m-20m.	Excluding southeastern corner: suction caissons and drag anchors, the lowest cost and simplest anchor solutions, may only start to become feasible at upper end of depth range (20m). Local incisions in the bedrock corresponding to increased thickness of quaternary deposits may increase number of anchor solutions required within the PDA. Southeastern corner: anchor types potentially restricted to drilled piles and gravity anchors.	
Strength of bedrock for anchor installation.	Weak rock types: Tertiary interbedded. Strong rock types: Palaeozoic sedimentary.	May be feasible to install piles by driving or DDD techniques in Tertiary interbedded bedrock. If installation is by drilling, higher relative progress rate. Piling into Palaeozoic sedimentary bedrock by drilling. Potential for very slow progress rates.	
Wave loading for installation / O&M.	2m – 2.5m.	Moderate mean sea state. Weather windowing for some more sensitive installation activities will be challenging.	
Metocean conditions for structural feasibility.	$13m < H_{s\_50yr} < 16m$ and $42.5m/s < V_{ref} < 50m/s$.	H_{s_50yr} consistent with moderate site conditions and or V_{ref} below wind turbine class I reference but above class II reference.	
Presence of shallow gas.	Pockmarks identified as potentially present.	Pockmarks may be present, indicative of active or historic seepage. Pockmarks may cause uneven seabed conditions that may be unsuitable for certain anchor types.	
Combined anchor risk.	n/a	 The combination of *depth to Bedrock* and *strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*. These three risks are considered additive as both *depth to bedrock* and *strength of bedrock for anchor installation* affect the capacity of the anchorage system and *metocean conditions for structural feasibility* affects the demand on the anchorage system.	

The RAG maps and underlying data for PDA 3 are shown in Table 36, which provides more detail on the physical and metocean conditions that fed into the risk ratings for PDA 3. Larger maps of the underlying data can be found in Appendix B.

Table 36 RAG maps and underlying data for PDA 3

Risk factor	RAG map	Underlying data (see Appendix B for larger maps)
Seabed depth.		 Seabed depth (m) 50 - 70 70 - 120 Range in PDA: 68m to 85m
Depth to bedrock.		 Quaternary thickness (m) < 5 5 - 20 20 - 30 30 - 50 > 50 Range in PDA: 0m to >50m
Strength of bedrock for anchor installation.		 Bedrock lithology Palaeozoic Sedimentary Tertiary interbedded
Wave loading for installation / O&M.		 Mean annual significant wave height, H_s (m) 2.1 – 2.4 Range in PDA: 2.1m to 2.3m
Metocean conditions for structural feasibility.		 50-year extreme significant wave height, H_{s_50yr} (m) 13.001 - 14 Range in PDA: 13m to 14m

		 Range in PDA: 46.9m/s to 47.2m/s
Presence of shallow gas.		 

7.4 Project Development Areas summary statement

Through TCE's broader spatial refinement process (not included within this scope or report), three PDAs of 1.5GW capacity were identified. Sections 7.1 to 7.3 provide a summary of the risk assessment for each of the 3 PDAs.

- PDA 1 was rated as AMBER for the average maximum risk rating across the all the key engineering risk categories. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock*, and *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).
- PDA 2 was rated as AMBER for the average maximum risk rating across the all the key engineering risk categories. An area of RED risk was identified towards the north of the PDA, driven by *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).
- PDA 3 was rated as AMBER for the average maximum risk rating across the all the key engineering risk categories. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock* and *strength of bedrock for anchor installation* as well as the *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

Table 37 Summary of key engineering risks by PDA

PDA	Seabed depth	Depth to bedrock	Strength of bedrock for anchor installation	Wave loading for installation	Wave loading for O&M	Metocean conditions for structural feasibility	Presence of shallow gas	Combined anchor risk	Maximum risk
1									
2									
3									

The engineering risks associated with the 3 PDAs were assessed and are summarised above, based on the information and data available and the high-level assessment undertaken, each of the three PDAs were considered to have an average maximum risk rating of AMBER, indicating a level of technical risk which **may** be complex and / or costly to mitigate may be encountered. Each PDA also included a smaller area assessed as RED risk, indicating there were smaller areas within each PDA that were considered to have a level of technical risk which will **likely** be complex and / or costly to mitigate.

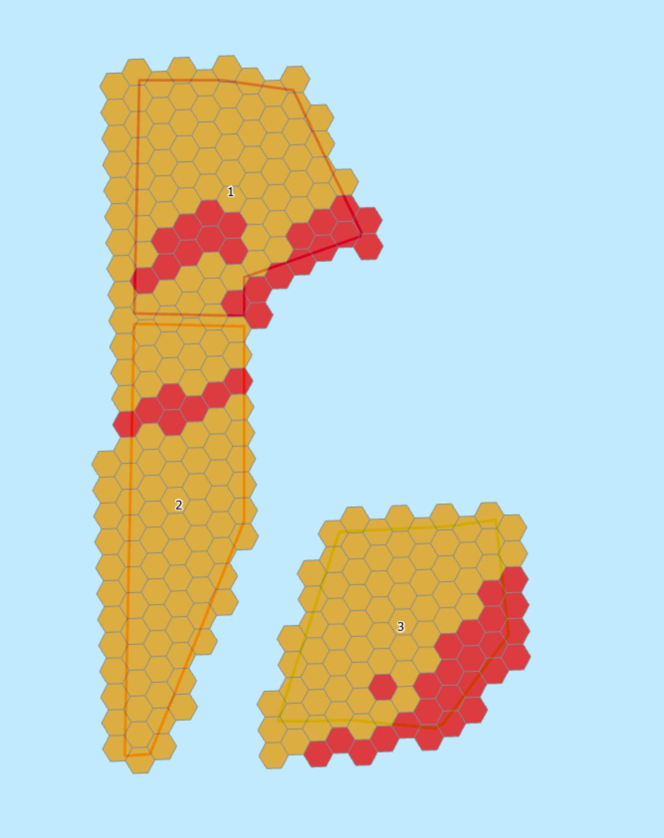


Figure 23 Maximum risk across the PDAs

This high-level assessment has not found the PDAs to be unviable, however site specific surveys, assessments and evaluation of risks is required to confirm this, noting the limitations in the assessment methodology set out in this report.

Across the PDAs, there were a range of technology options (support structure, anchor and moorings) considered suitable to the PDA characteristics.

8. Conclusions

8.1 RAoS risk summary

The high-level risk review conducted in Phase 1 indicated that four of the five RAoS (A, B, C and D) were rated AMBER, considering the average maximum risk (that being the spatial-average across the RAoS of the highest-rated risk in each hex-cell). The risk criteria which governed this conclusion were *seabed depth*, *wave loading for installation*, *wave loading for O&M* and *metocean conditions for structural stability*, all of which were rated as AMBER across all four of these RAoS.

The remaining RAoS (E) was rated RED considering the average maximum risk across all the key engineering risk categories. The risk criteria which governed this conclusion were *depth to bedrock*, *wave loading for installation* and *wave loading for O&M* which were rated RED for RAoS E.

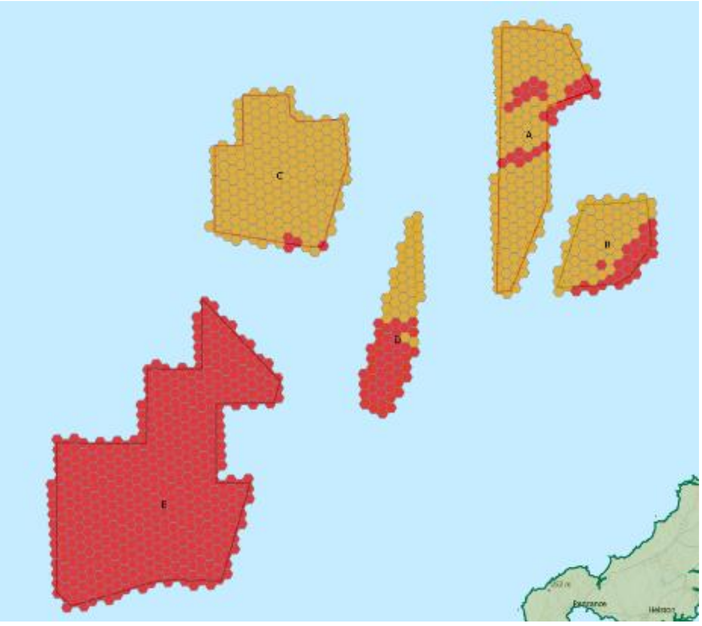


Figure 24 Maximum risk rating across all categories – RAG risk rating by hex-cell

As well as the key engineering risk categories a *combined anchor risk* category was created since certain risk categories were deemed to be related. Since *depth to bedrock* and *strength of bedrock for anchor installation* affects the capacity of the FLOW anchorage system and *metocean conditions for structural feasibility* affects the demand on the FLOW anchorage system, these key engineering risks were considered together in the *combined anchor risk*. All RAoS were deemed to be rated AMBER for the *combined anchor risk.* The risk criteria that governed this conclusion were *strength of bedrock for anchor installation*, rated in the lowest risk category (GREEN) across all RAoS and *metocean conditions for structural feasibility*, rated AMBER across all RAoS.

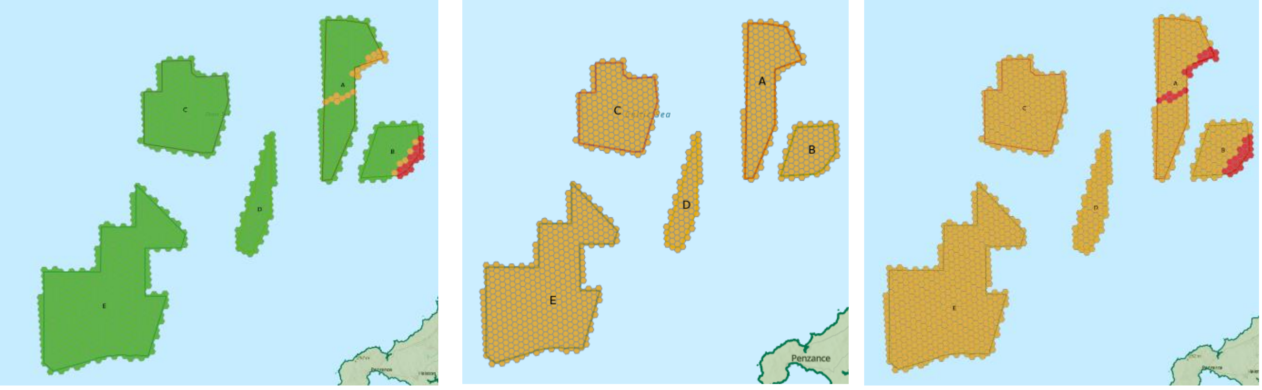


Figure 25 Strength of bedrock for anchor installation (left), metocean conditions for structural feasibility (middle) and combined anchor risk across the RAoS

The attributes of the RAoS assessed in the risk review were included in a high-level LCOE calculation completed as part of the SCALE modelling process. The LCOE results therefore provide a more granular review of the potential feasibility of floating offshore wind within the RAoS, while quantitatively taking into consideration the relative contribution of the various components of the floating technology (support structure, mooring and anchors) to the overall LCOE.

The results from the SCALE model indicated that the RAoS with lowest LCOE were areas A and B, followed by C and D, with E having the highest LCOE. This corresponded to a general correlation of increasing LCOE with increasing water depth, wave height, and metocean conditions, which become more onerous moving towards the southwest. The LCOE results are shown in Figure 26.

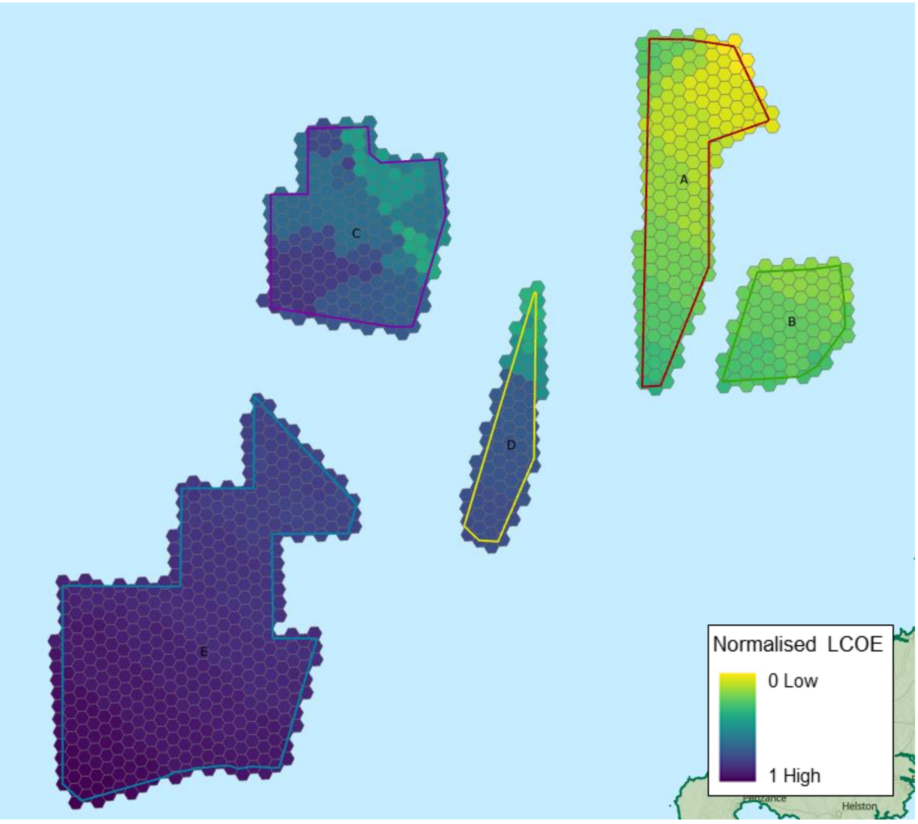


Figure 26 Summary of LCOE across each RAoS

The normalised LCOE values provided are suitable for relative assessment of the RAoS as part of this assessment only and should not be relied upon outside the purposes of this assessment. The output is based on the assumptions and subject to the limitations outlined in Section 6.

Anchor supply and installation made a lower contribution to LCOE than the other parts of the floating technology, and therefore a trend in LCOE with ground conditions (e.g. depth to bedrock) was less apparent. The effect of ground conditions on LCOE was most pronounced in RAoS C where there was the greatest variability in quaternary deposits and therefore depth to bedrock.

Based on the analysis conducted, all of the FLOW technologies (support structure and mooring combinations) considered were found to be likely feasible across all RAoS. The lowest cost floating technology type selected across the whole SCALE model was the steel TLP with either driven or drilled piled anchors, depending on the depth to bedrock, based on the assumptions, inputs and analysis of the SCALE model at the time of the assessment. This was driven by the lower CAPEX cost associated with the floating components when compared with the alternative technologies.

8.2 PDA risk summary

Through TCE's broader spatial refinement process (not included within this scope or report), three PDAs of 1.5GW capacity were identified. Section 7 provides summary of the risk assessment for each of the 3 PDAs. This high-level assessment did not identify any specific reason to consider any PDA – or any part of a PDA – technically unviable. Some areas of the PDAs had areas of red risk identified which should be reconsidered at project level.

PDA 1 was rated as AMBER based on average maximum risk rating, that being the spatial-average of the highest rating in each hex-cell. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock* and *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

PDA 2 was rated as AMBER for the average maximum risk rating. An area of RED risk was identified towards the north of the PDA, driven by *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

PDA 3 was rated as AMBER for the average maximum risk rating. An area of RED risk was identified on the south-east edge of the PDA, driven by *depth to bedrock* and *strength of bedrock for anchor installation* as well as the *combined anchor risk* (*strength of bedrock for anchor installation* with *metocean conditions for structural feasibility*).

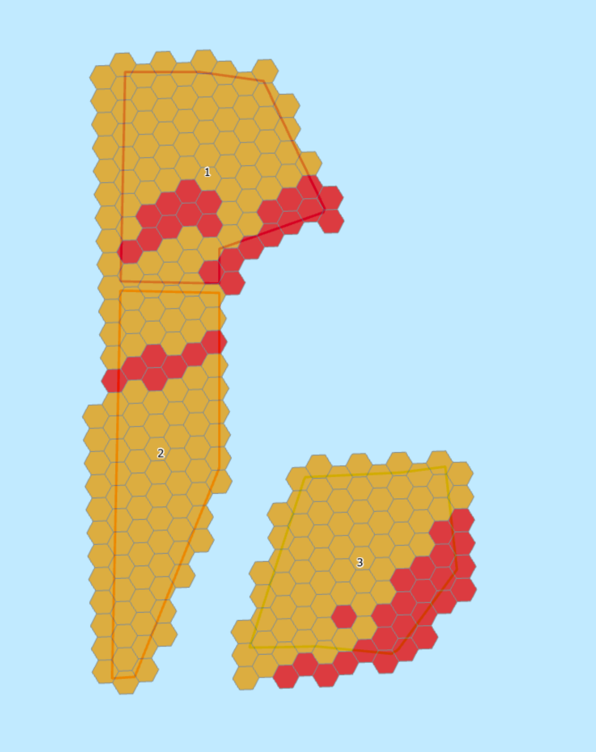


Figure 27 Maximum risk rating across the PDAs

8.3 Final Remarks

This assessment was used to inform the spatial refinement process in conjunction with various other refinement exercises and assessments undertaken by TCE and others.

The scope of work summarised in this report and associated geospatial output aimed to provide TCE with a high-level understanding of the potential technical and commercial viability of the RAoS and PDAs. This was informed by a high-level technical engineering risk assessment covering physical environmental risks and the implications of these risks on overall relative levelised cost of energy (LCOE).

It should be noted that the scope of work and associated output is in nature high-level risk identification and qualitative. The results of the RAG assessment are based on third-party data which has not been subject to detailed review as part of this study. The results are therefore dependent on the accuracy and the completeness of the data provided by third parties and the agreed assumptions are inherently subject to uncertainty.

As well as being high-level, this assessment is precautionary in nature: for a PDA to be rated GREEN based on average maximum risk, it would have to have idealised characteristics unlikely to be seen at very many – if any – FLOW sites in the UK or worldwide. The result (some PDAs rated AMBER with areas of RED risk) is felt to be an appropriate conclusion, given the relative immaturity of floating offshore wind technology and the quality of data available. In this context, it is also important to re-iterate that this assessment has found no reason to categorise any PDA – or any part of a PDA – as technically unviable.

It is expected that potential bidders will carry out an independent review of the PDAs as part of submitting a Leasing Round 5 bid. The assumptions and limitations set out in this report should be further assessed and considered through the development and design of a Round 5 project through site specific survey and assessment.

Appendix A

Data sources and references

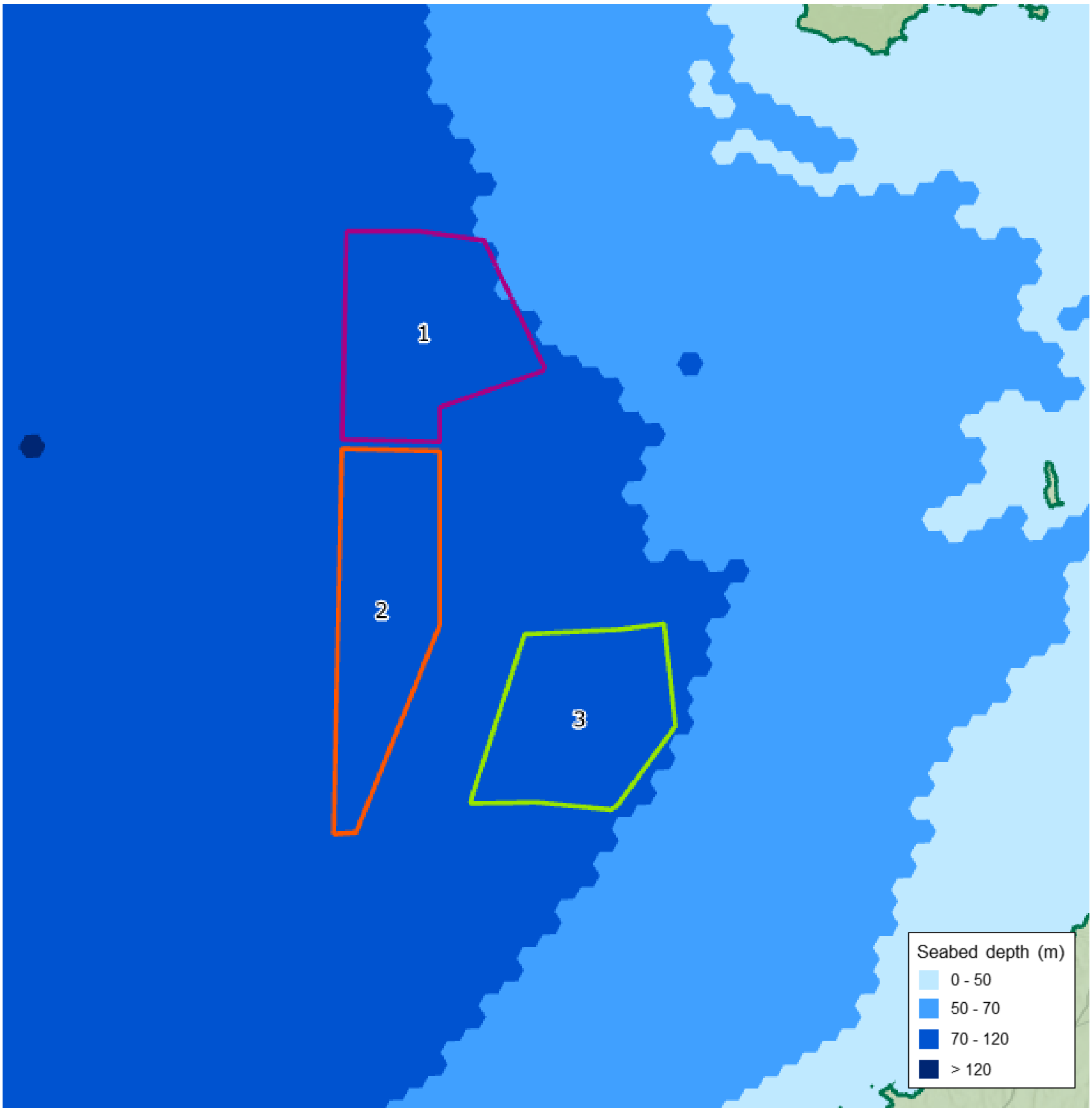
Ref	Data source or geospatial dataset	Type	Data owner
[1]	BGS (2014). Geological Constraints on Development across the UK Continental Shelf. CR/14/050	Methodology report	BGS
[2]	BGS (2014). Geological Constraints on Offshore Infrastructure. Energy CR/14/073	Methodology report	BGS
[3]	BGS (2015). BGS Input to The Crown Estate Levelised Cost of Energy model update 2015. CR/15/022	Methodology report	BGS
[4]	BGS (1991). North Celtic Sea 1:250 000 Series. Quaternary Geology	Geological map	BGS
[5]	BGS (1994). Quaternary Geology around the United Kingdom (South Sheet)	Geological map	BGS
[6]	BGS (1991). Geology of the United Kingdom, Ireland and the adjacent continental shelf (south sheet). 1:1M scale	Geological map	BGS
[7]	BGS (2014) BGS Bedrock Summary Lithologies.	Geological factor map	BGS
[8]	BGS (2015). Quaternary Thickness (with 2015 updates to include 20m and 30m contours)	Geological factor map	BGS
[9]	BGS (2015). Quaternary Deposits Summary Lithology (with 2015 updates to include sub-division of Diamict and Undifferentiated deposits)	Geological factor map	BGS
[10]	BGS (2015). Rugosity (with 2015 updates)	Geological factor map	BGS
[11]	BGS (2014). Shallow Gas Potential	Geological factor map	BGS
[12]	BGS (2014). Pockmarks Distribution	Geological factor map	BGS
[13]	Ordtek (2022). Phase 1: Project UXO Hazard Assessment. Celtic Sea – Search Areas 1 – 5. JM7093_Celtic Sea_UXO_Phase 1_HA_V1.0.	Report	Ordtek
[14]	Ordtek UXO geospatial datasets	Geospatial data	Ordtek
[15]	European Subsea Cables Association (2023). ESCA Guideline No.6. The Proximity of Offshore Renewable Energy Installations & Subsea Cable Infrastructures	Report	ESCA
[16]	The Crown Estate (2022). Celtic Sea Tele Cables RAG	Geospatial data	TCE
[17]	MetOceanWorks (2022). Metocean Data Overview Celtic Sea FLOW, 22 April 2022, Reference: TCE_C00001_R02_Metocean_Data_Overview	Report	MetOceanWorks
[18]	MetOceanWorks (2022). Metocean data	Geospatial data	MetOceanWorks
[19]	ABPmer (2018). SEASTATES Northwest European Shelf Wave Hindcast Model	Geospatial data	ABPmer
[20]	EMODnet (2020). Bathymetry World Base Layer	Geospatial data	EMODnet

Ref	Data source or geospatial dataset	Type	Data owner
[21]	International Electrotechnical Commission (2019), International Standard ICE 64100-1:2019	Report	IEC
[22]	Offshore Renewable Energy Catapult (2021). Mooring and Anchoring Systems – Market Projections	Report	OREC
[23]	National Grid Electricity System Operator (2023). Five-Year Projection of TNUoS Tariffs for 2029/30 to 2033/34	Report & Data	ESO
[24]	Arup (2020). Future Offshore Wind Scenarios (FOWS) to 2050 available online https://www.futureoffshorewindscenarios.co.uk/	Report & Data	Various
[25]	BloombergNEF (2023). Floating wind on course to boom to 28 gigawatts by 2035	Report	BloombergNEF
[26]	Met Office (2020). 30-year average wind speed	Geospatial data	Met Office

Appendix B

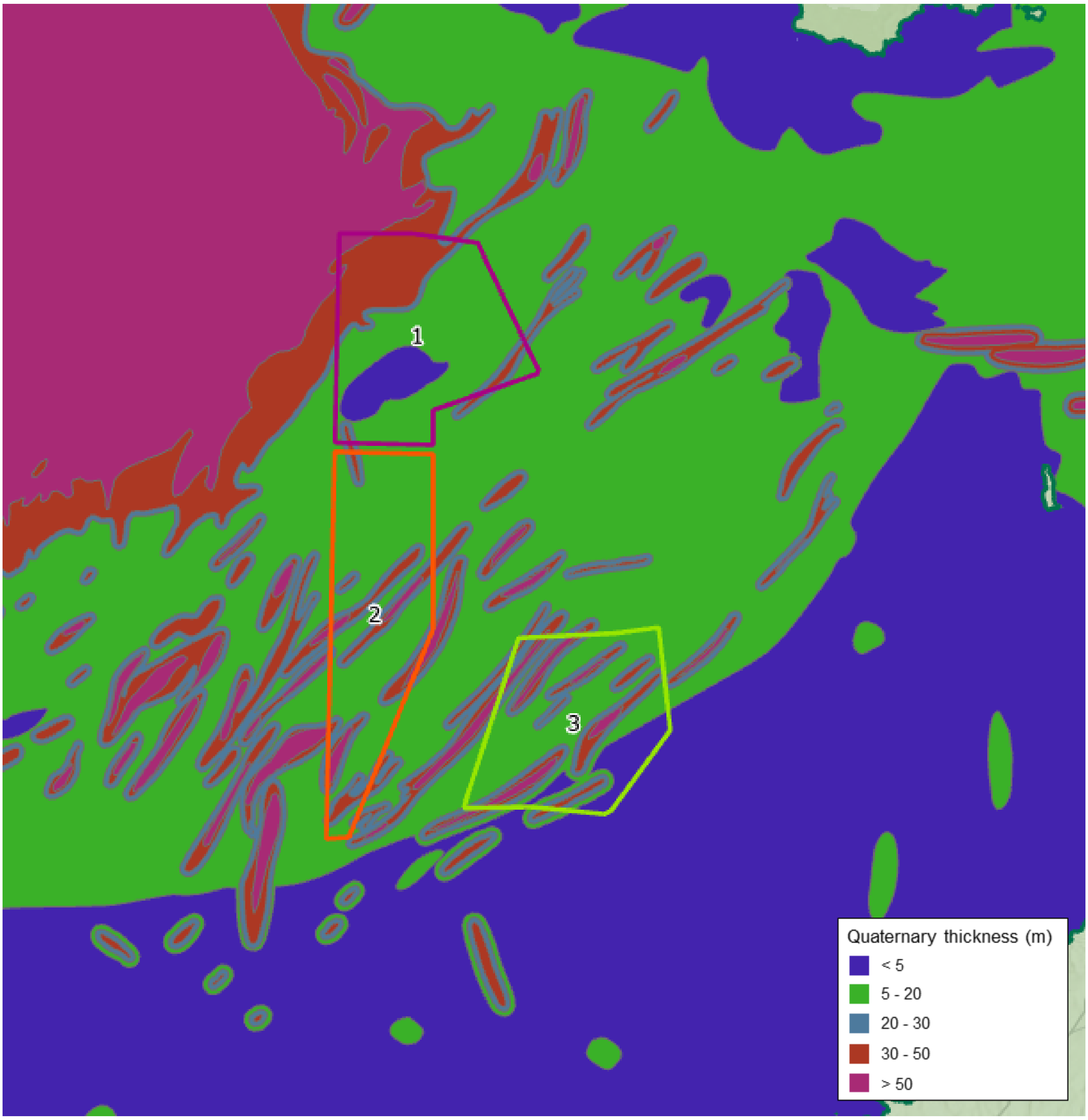
Data maps for PDA risk assessment summary

B.1 Seabed depth



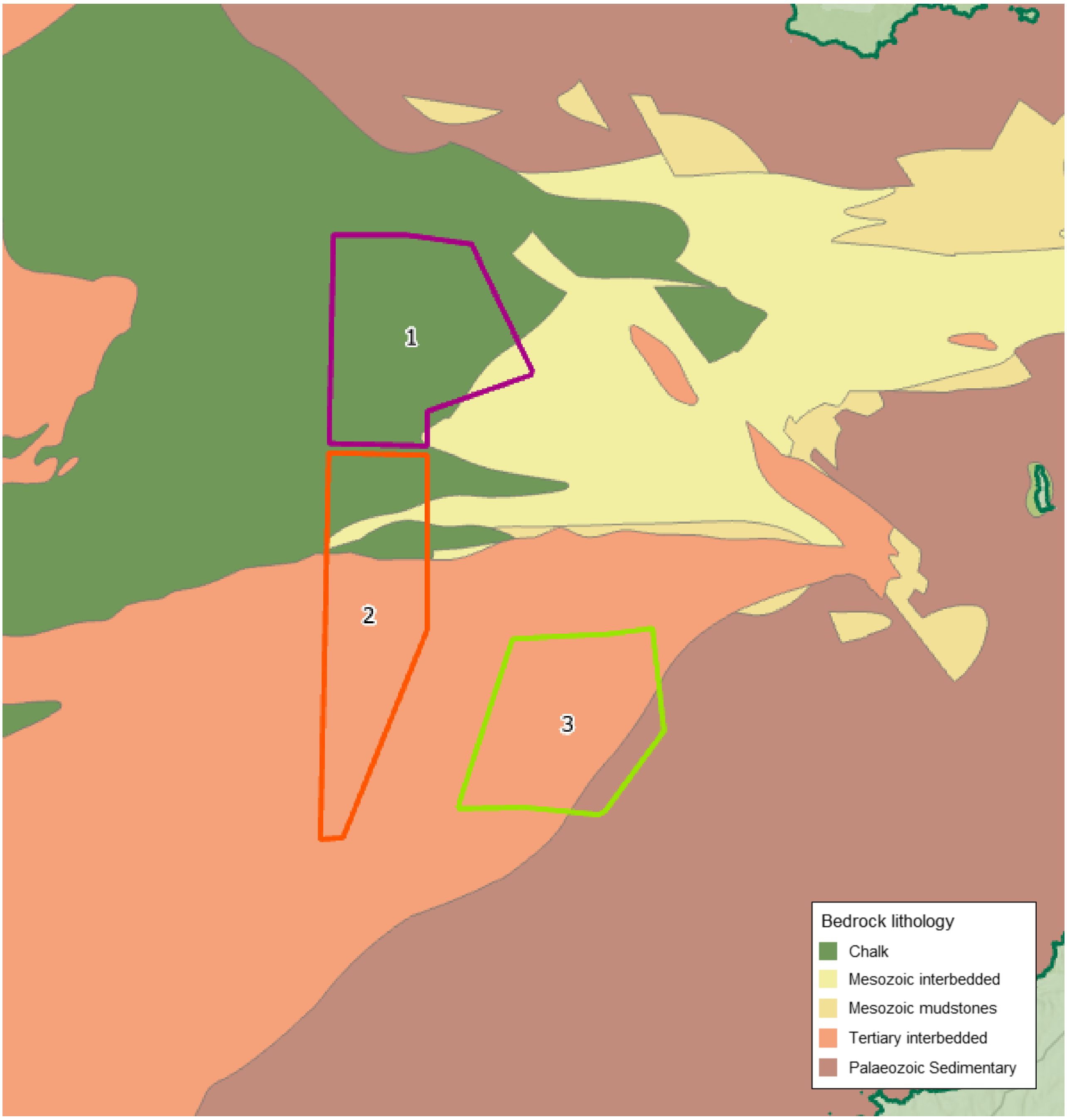
The seabed depth data has been taken from [20] and has been processed by Arup to create a hex-cell seabed depth dataset based on the depth ranges used for the RAG assessment criteria.

B.2 Quaternary thickness



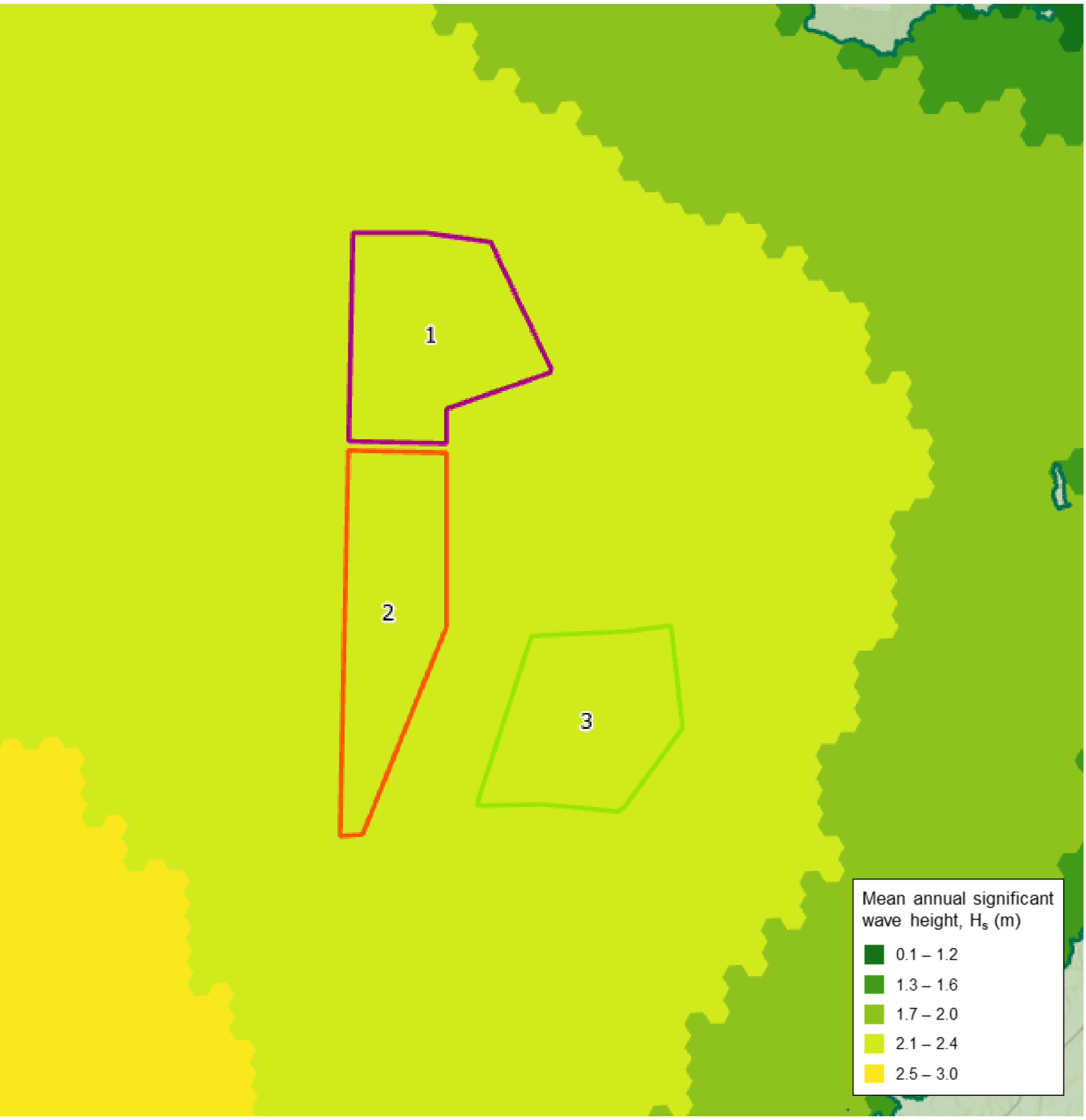
The quaternary thickness data is as provided in [8].

B.3 Bedrock lithology



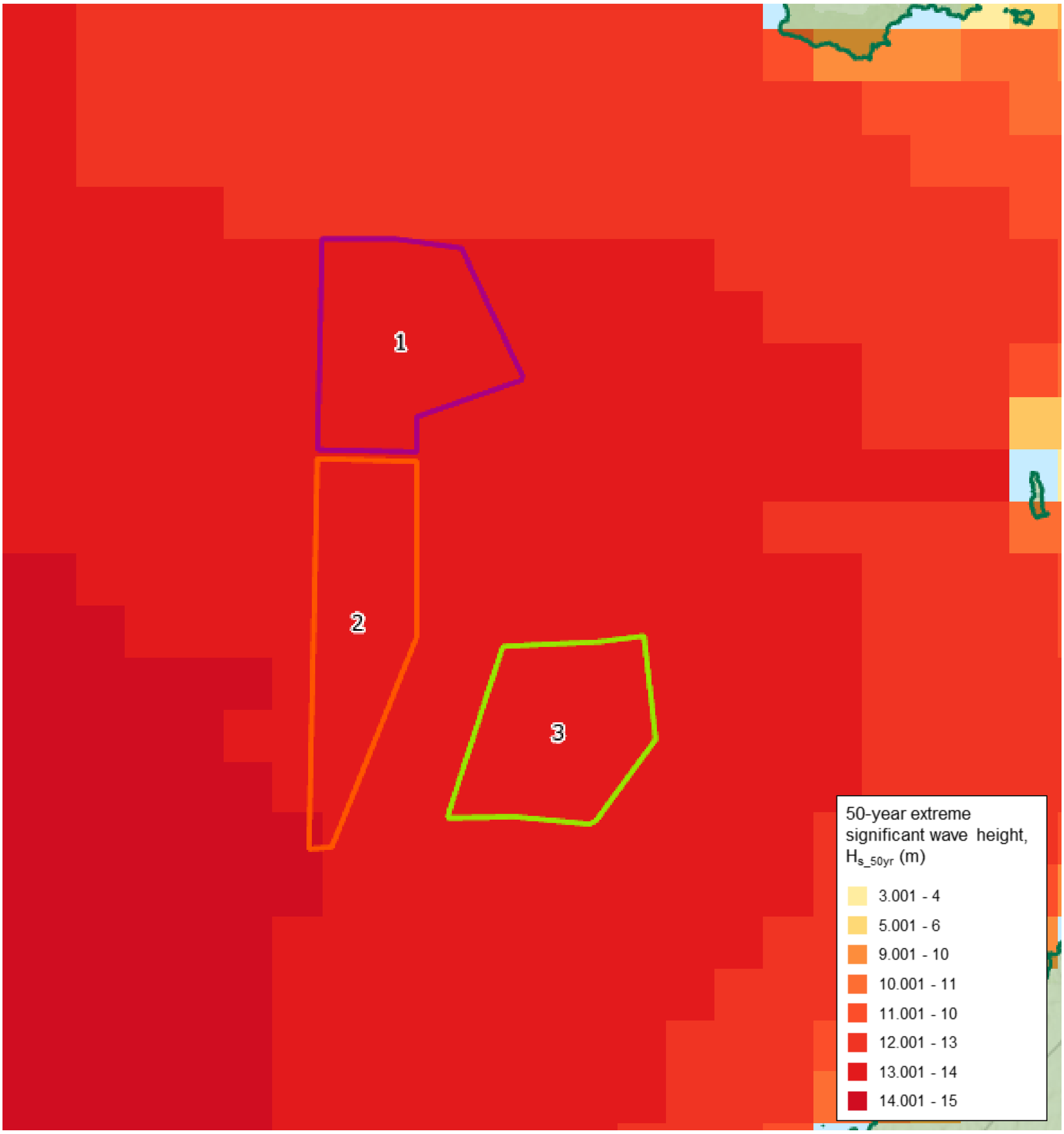
The bedrock lithology data is as provided in [7].

B.4 Mean annual significant wave height



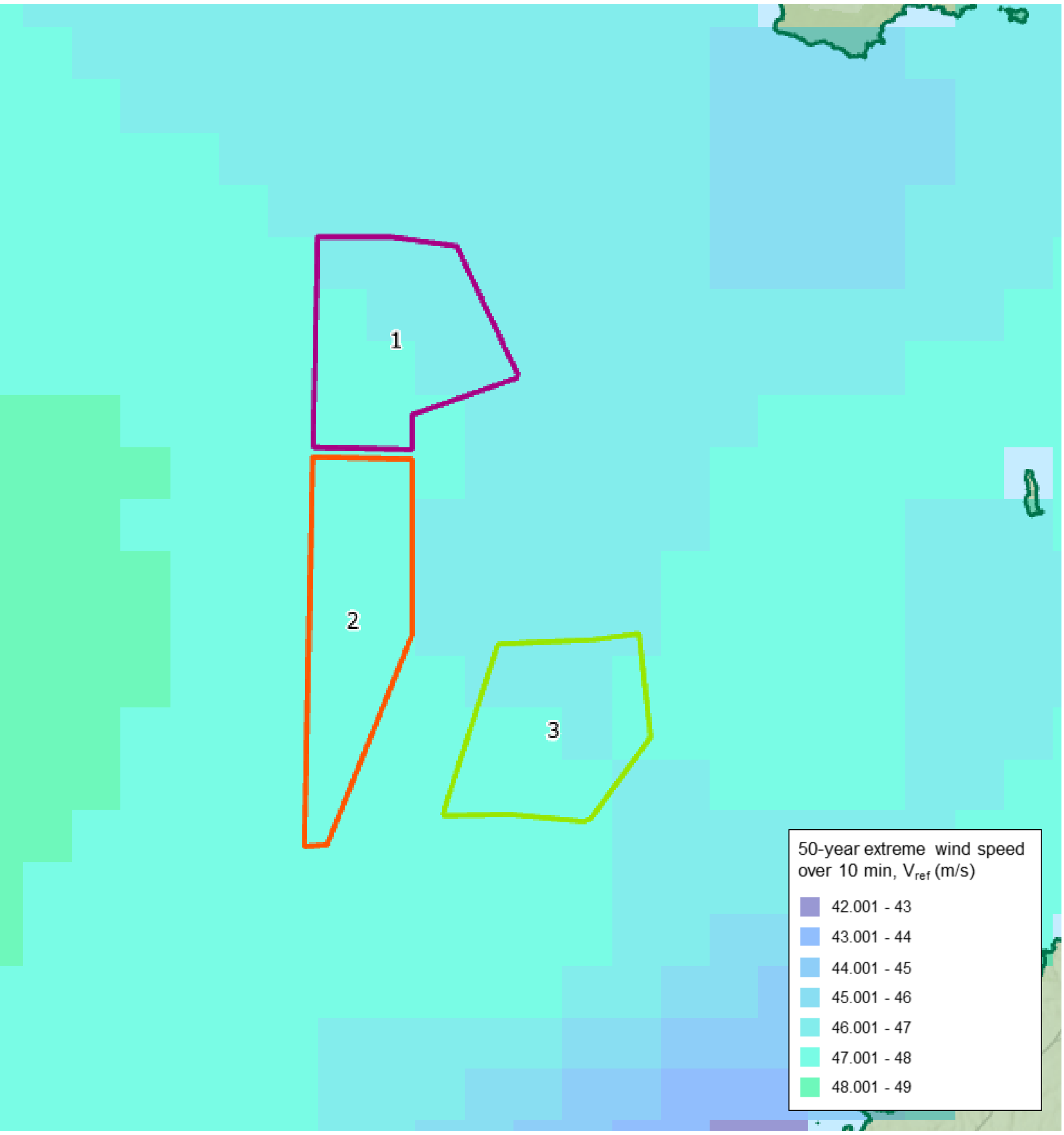
The mean annual significant wave height has been calculated from [19]. The data shown is the mean of all the hourly significant wave height values in the 31-year hindcast period provided in [19], the data has been processed by Arup to create a hex-cell mean annual significant wave height dataset based on the mean annual significant wave height ranges used for the RAG assessment criteria.

B.5 50-year extreme significant wave height



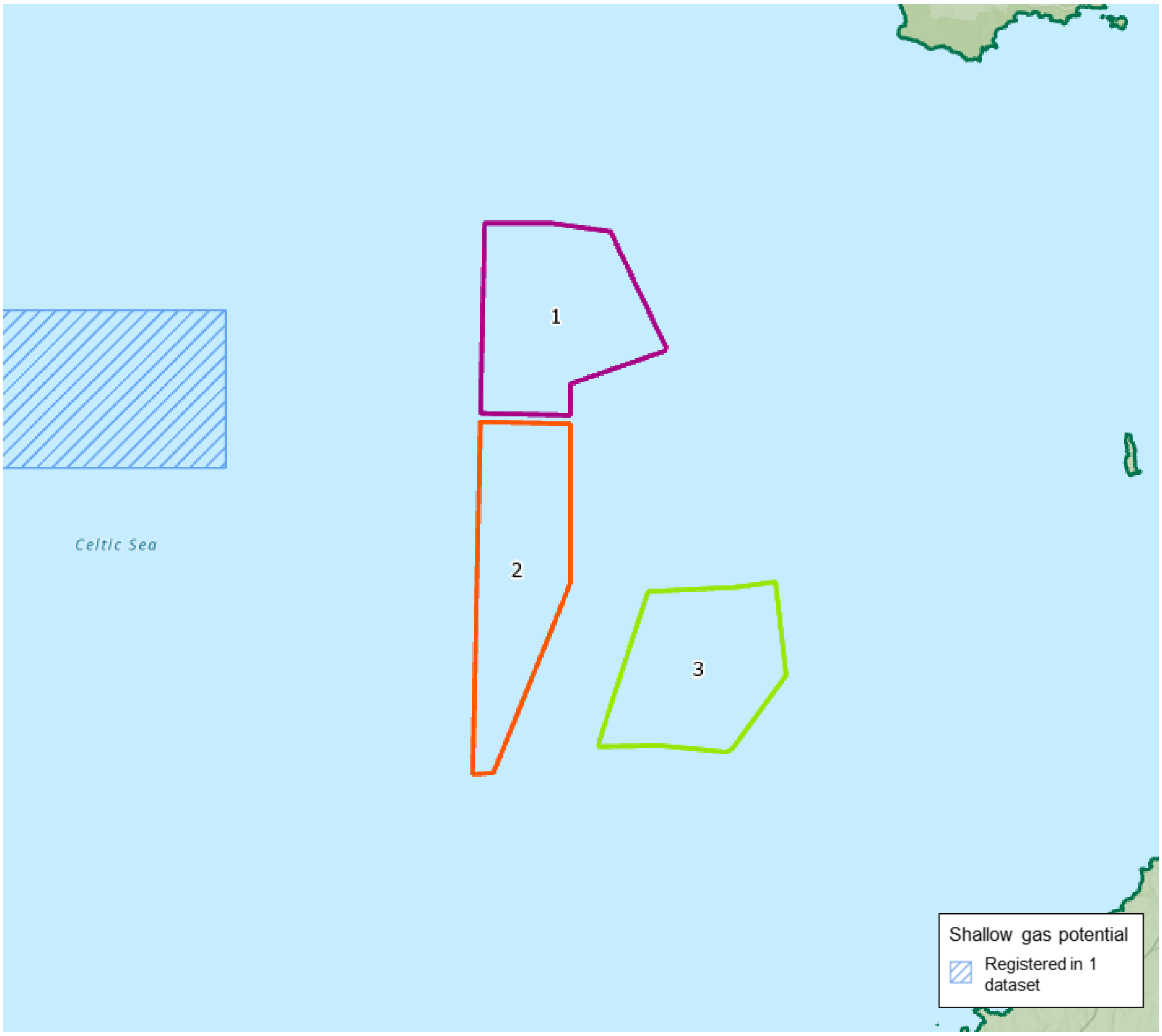
The 50-year extreme significant wave height is as provided in [18]. It is the extreme value of significant wave height expected over 50 years.

B.6 50-year extreme wind speed over 10 minutes at 150m



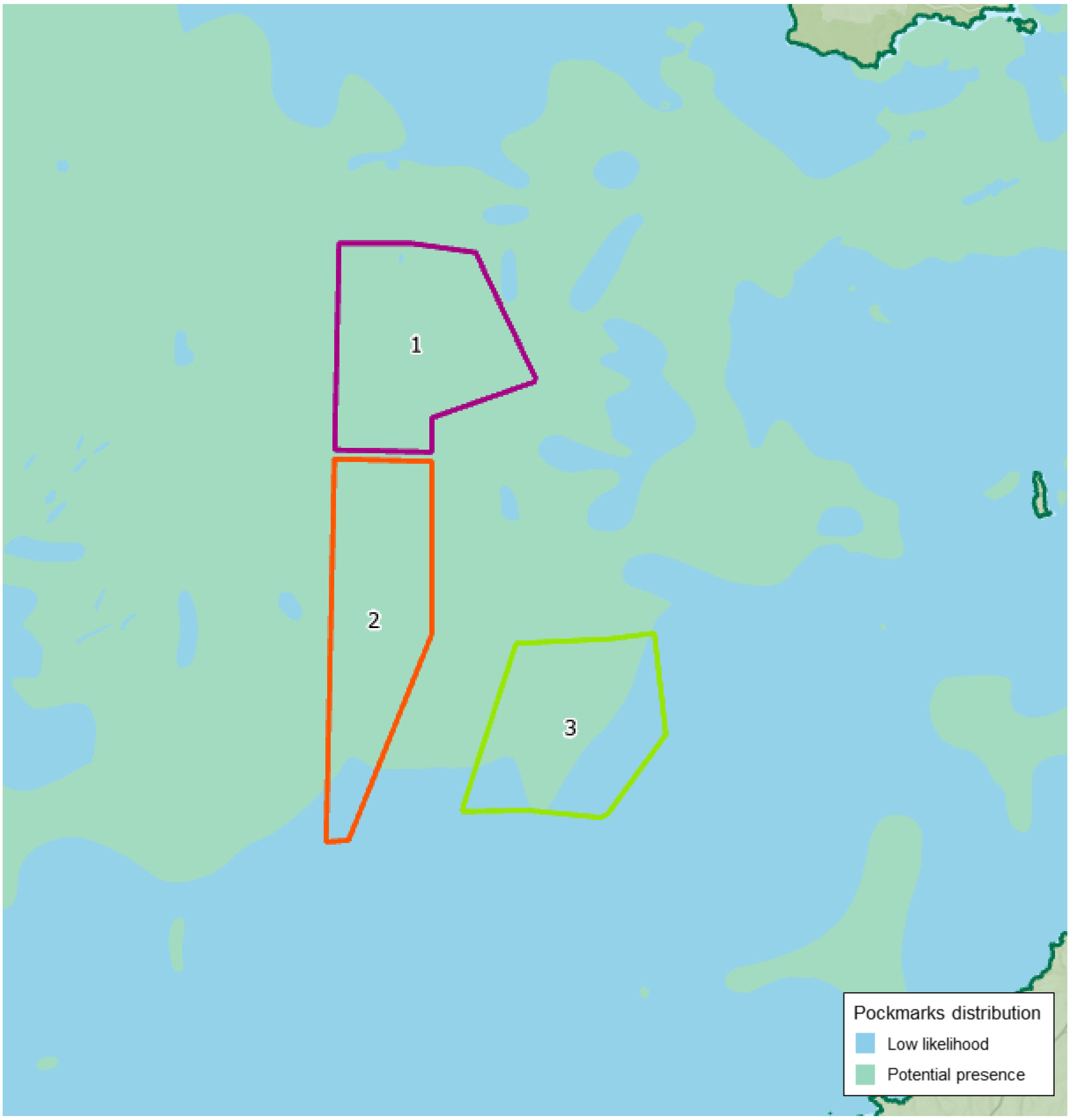
The 50-year extreme wind speed over 10 minutes at 150m above sea level is as provided in [18].

B.7 Shallow gas potential



The shallow gas potential data is as provided in [11].

B.8 Pockmarks distribution



The pockmarks distribution data is as provided in [12].