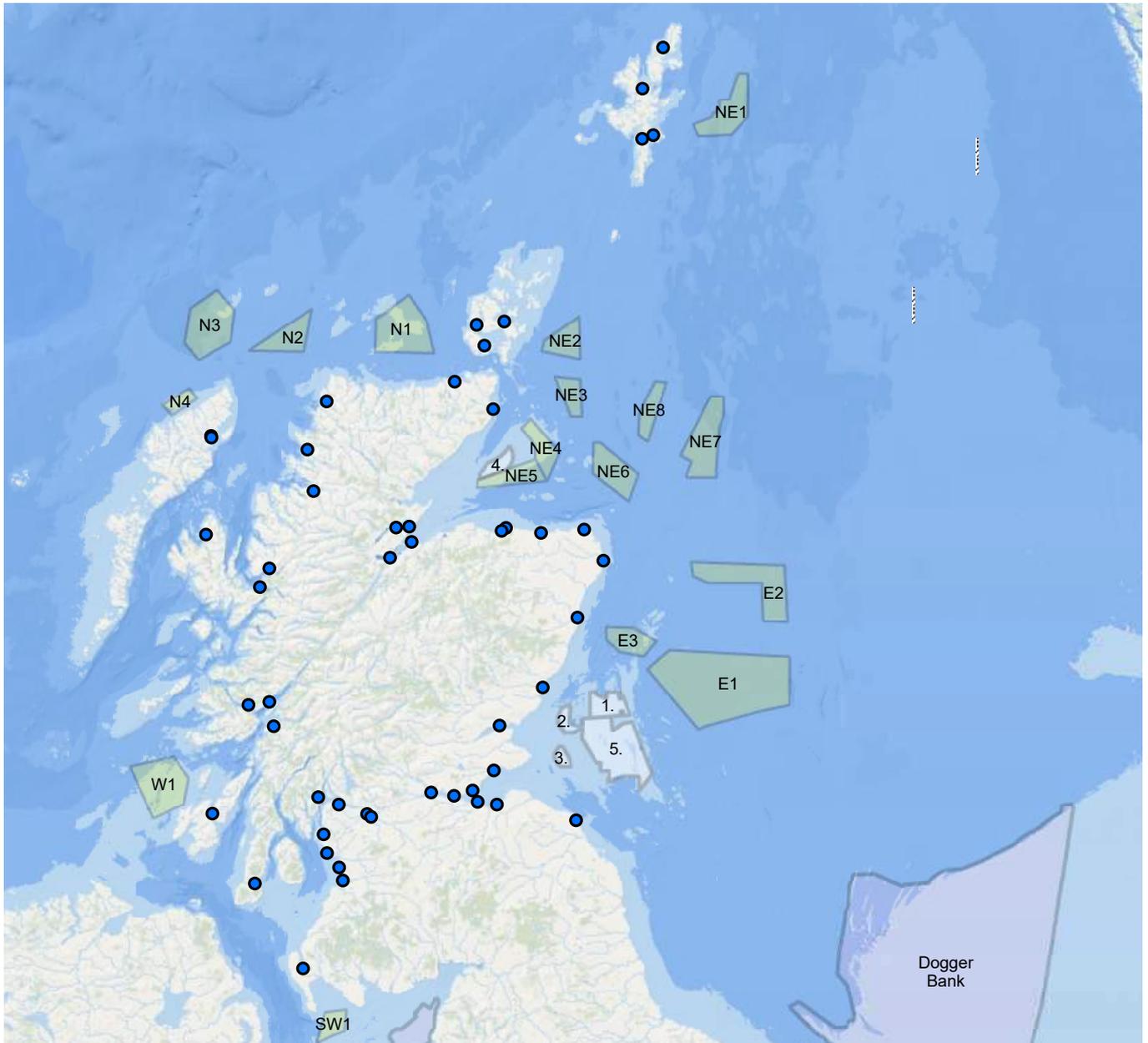


Crown Estate Scotland

Ports for offshore wind

A review of the net-zero opportunity for ports in Scotland

Issue | 2nd September 2020



This report takes into account the particular instructions and requirements of our client.

It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

Job number 270881-00

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Foreword

As Scotland seeks to build a green economic recovery from the current pandemic it is vital that we keep our sights firmly set on our commitments to get to Net Zero by 2045.

This will involve ingenuity in how to make the most of our natural resources and, as a result, build a more sustainable future. We are fortunate in Scotland to have some of the best natural marine resources in the world, and finding ways of unlocking their potential will help us tackle climate change and futureproof our economy simultaneously. Offshore wind offers us a potential path for doing exactly that.

We recently fired the starting pistol on Scotland's first offshore wind leasing round for a decade, via ScotWind Leasing, which forms part of our wider joined up approach to help create an opportunity to tap in to the potential our marine resources have for the expansion of offshore wind. This includes work to promote and enhance supply chain development, through measures included in our leasing process, as well as making investments in facilities such as the Zero Four site in Montrose, capable of hosting vital support bases for future projects.

While ScotWind is a critical first step in securing the opportunity which lies ahead, it will only work if various other steps are taken alongside this. One of those steps is ensuring that Scotland's ports are ideally equipped and ready to support the rapid expansion of offshore wind and play host to the major projects we hope to see in the years to come.

This report seeks to provide a route map for doing exactly that, by examining the future trends, needs and requirements of the offshore wind sector, and highlighting some of the ways in which our ports can maximise the benefit from the opportunity that is within reach.

Scotland, of course, already has a strong and thriving ports sector, and a world leading energy skills knowledge base established throughout decades of oil and gas exploration. Now, as we make the transition to a Net Zero future, we have the opportunity to build understanding between the ports and energy industries on what each other's needs are likely to be in the years to come. Only through this increased understanding and collaboration can we be satisfied that both sectors are making the most of the prize on offer.

This will be a collective effort, a Team Scotland effort, which will involve public and private sectors working closely together on a shared vision.

Such collaboration between public and private sectors has already led to the creation of the Scottish Offshore Wind Energy Council, and the ScotWind Leasing process will ensure greater transparency than ever before in how offshore wind developers will engage with their potential supply chain partners.

In order to move forward though we need to have the best possible understanding of what a thriving offshore wind sector in Scotland will look like, and port infrastructure is a vital piece of that jigsaw. We also need to understand, and have an honest debate about, what the main challenges and opportunities are going to be in the future partnership between ports and offshore wind developers.

That means building a momentum of activity around issues like the use of marshalling ports, creating a strategic approach for how offshore wind port facilities are established, and looking at how to support the development of potential operation and maintenance facilities around Scotland.

We start this journey from a position of strength, and I am optimistic that we can build on this and ensure that Scotland's ports can write an exciting new chapter and help us deliver a Net Zero future.



Amanda Bryan
*Chair,
Crown Estate Scotland*



Executive summary

Purpose

Crown Estate Scotland (CES) commissioned Arup to undertake a review of the suitability of port facilities in Scotland to support future offshore wind development. This report provides a summary of the study. Its purpose is to provide;

- a summary of the assessment of the capability of the ports sector to support the offshore wind industry to 2040, at a strategic Scotland-wide level;
- identification of challenges and opportunities for port infrastructure provision in Scotland, to contribute to the decision-making processes of parties across the industry; and
- recommendations for consideration by CES and the wider public sector specifically. It was not an objective of the study to provide recommendations for consideration by private sector parties in the ports and offshore wind sector. Nonetheless, findings will be relevant to them.

Methodology

A baseline review of port use and requirements for offshore wind was undertaken. The review considered recent major projects and possible future technology evolution, and took account of major components, logistics methodologies, and vessels drawing on examples from the UK and continental Europe. Three main port uses in support of offshore wind were considered: operations and maintenance (O&M), and the construction phase uses of marshalling/assembly and fabrication/manufacture¹. For the construction phase uses, the study focussed on foundation and turbine components on the basis that these typically drive the largest share of port use on a project. Fixed-bottom and floating offshore wind technologies were considered. The baseline review provided the basis for assessment of the capability of ports.

All existing ports and harbours in Scotland with potential significance for offshore wind were considered in the study. A screening approach was used to focus data collection, and a mix of quantitative and qualitative assessment identified the ports with a minimum level of suitability for each offshore wind use, as well as those ports most likely to be suited to supporting future development of multiple future offshore wind projects. A range of port attributes were characterised, including existing technical capability, potential for upgrade and proximity to offshore development zones². Technical and operational criteria were considered in the study. Economic and social factors were not quantitatively considered. High-level projections for onshore laydown area demand, identified as a critical variable, were generated to inform the assessment.

The study was undertaken as a desk-based exercise utilising data from the public domain, CES and from three public sector partner agencies - Scottish Enterprise, Highlands and Islands Enterprise, and Transport Scotland³. Engagement with other third parties including the ports, offshore wind developers, investors, contractors and the wider supply chain was not within the scope of this study. It is recognised that this could be the key next step in further progression of the findings and recommendations presented in this study.

¹ A port supporting multiple marshalling/assembly and fabrication/manufacturing functions as exist in and are under development in some countries are commonly referred to as 'Integrated Manufacturing Hubs' or 'Co-located Manufacturing Hubs'.

² The offshore development zones considered in this study were the 16 Draft Plan Areas expected to be available for leasing in the forthcoming ScotWind process (as identified in the Draft Sectoral Marine Plan [1]), referred to as the ScotWind zones in this report; five pre-ScotWind Scottish windfarms under development, which did not have preferred ports announced as of November 2019; and the rest-of-UK Round 4 zones.

³ Arup was tasked with writing the report with input from Crown Estate Scotland, who commissioned the work. The report does not necessarily reflect the views of the other parties mentioned.

Findings

Headline finding

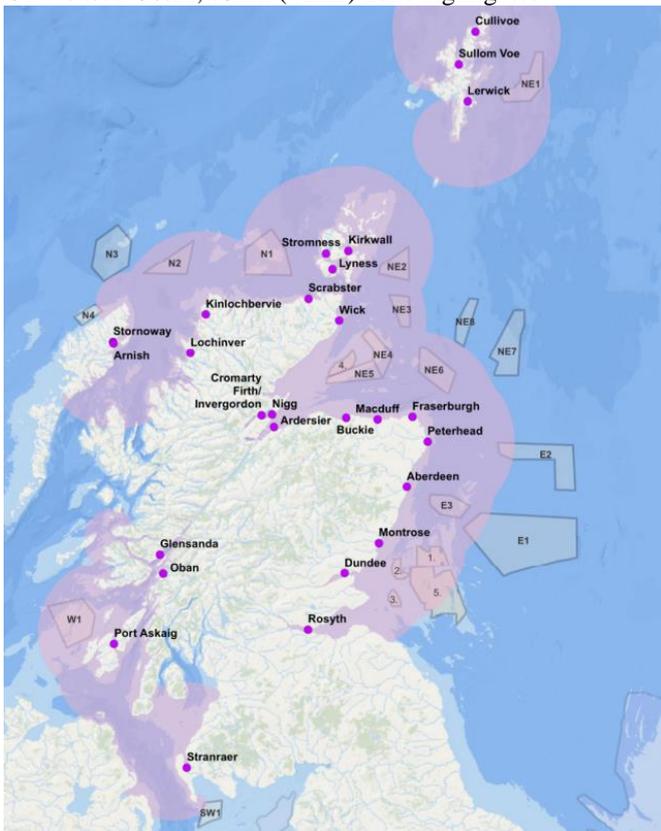
Scotland has good technical capability to support offshore wind port functions in some, but not all locations. However, we believe that there is a significant risk that existing port capacity will be insufficient to support the offshore wind build-out rates required in Scottish waters to meet the UK-wide net-zero target. There are multiple port locations which are likely to be suitable for development of additional capacity to address this risk. This is true for both the large construction phase uses of ports, and operations and maintenance (O&M).

Finding 1: Port capability and capacity for operations and maintenance (O&M)

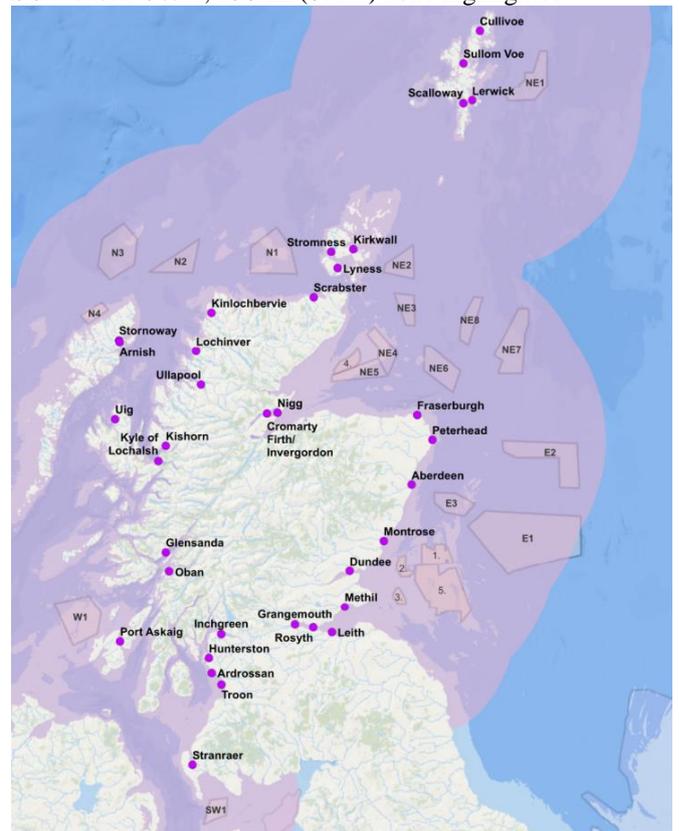
The locations and distribution of the ScotWind Leasing zones are such that a mix of smaller, shorter-range, Crew Transfer Vessel (CTV) and larger, longer-range, Service Operation Vessel (SOV) based O&M strategies will likely be required. We expect there to be significantly greater SOV use than in the offshore wind industry to date, based on distance from port alone. Of the 21 pre-ScotWind and ScotWind zones considered, six have no ports within an assumed ideal sailing distance for CTVs, and a further seven are within this distance of only one or two ports.

Figure 1: Ports meeting the assumed minimum hard criteria for O&M uses, with assumed ideal sailing distance indicated⁴. Refer to Appendix C for full page versions.

CTV based O&M, 75km (41nm) zone highlighted



SOV based O&M, 150km (81nm) zone highlighted



There is broadly adequate technical port capability to support both CTV and SOV based O&M strategies. Capability is well distributed, with appropriate ports available for all the offshore development zones considered. However, we expect capacity to be constrained due to existing port uses and the scale of future offshore wind

⁴ Hard criteria were set based on judgement of minimum requirements that would indicate a port had reasonable potential for use for multiple projects and consider existing capability and upgrade within reasons. If a port does not meet these it does not mean that the port would not or could not be used on an individual project. All businesses have their own decision-making criteria. See main body of report for more details.

development, and that infrastructure upgrades will be justified in multiple locations to facilitate expansion of both berthing/water space and areas for associated onshore facilities.

Finding 2: Port capability and capacity for large construction-phase uses (marshalling/assembly and fabrication/manufacturing)

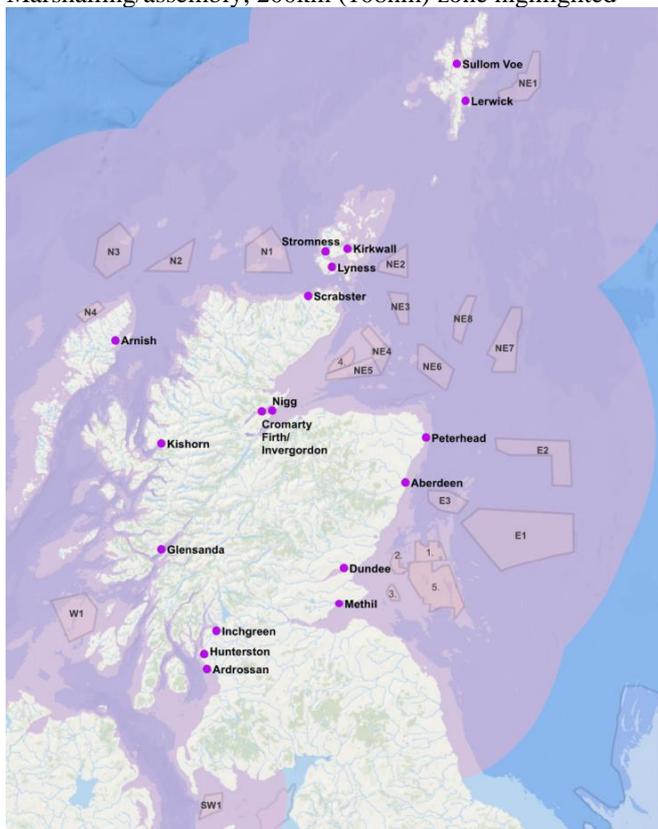
Marshalling/assembly ports have been used as local final staging points between globally distributed supply chains and offshore sites on recent major projects across the UK and continental Europe. They are a key feature of the logistical methodologies, approach to risk management, and contractual arrangements of these projects and as such their use can be inferred to have been a contributing factor to increasing project scale and lower project costs.

Scotland has ports with adequate technical capability to support marshalling/assembly. However, they are limited in number, capacity and geographic distribution when compared to the future ScotWind zones. Several existing ports, although meeting minimum hard criteria, do not currently provide the same standard of infrastructure as is typically desired by some offshore wind developers and contractors to limit constraints on a project; for example onshore storage area to accommodate a buffer stock of a reasonable percentage of components, or unrestricted water depth of 10-12m below Chart Datum that is sufficient to allow the majority of the North Sea installation and transport vessel fleet to tender for work on a project.

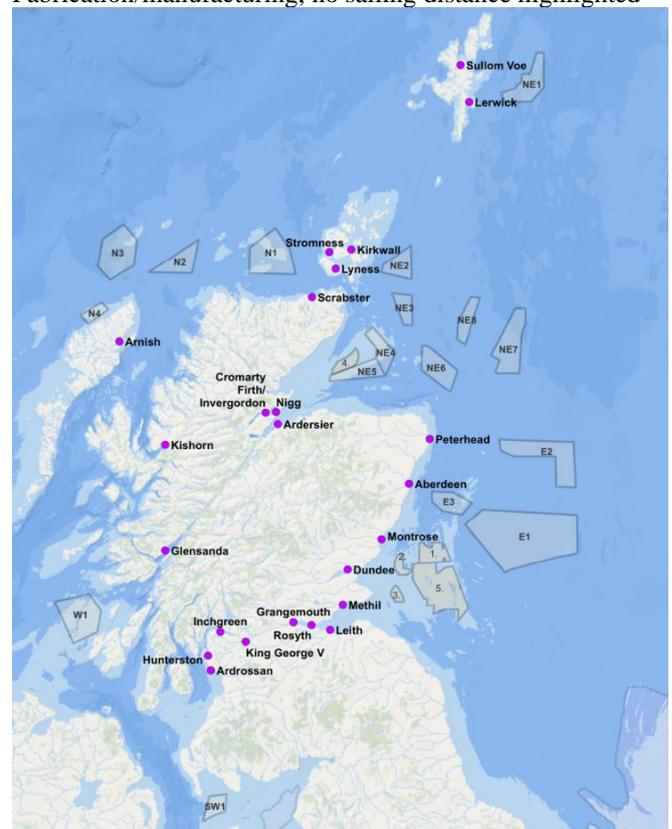
A small number of ports in Scotland host a single offshore wind manufacturing function. Port capability for a single manufacturing function is typically less critical than for marshalling/assembly. For example, 24-hour vessel access irrespective of tides may be less critical if components are being shipped to an intermediate location and not directly to the offshore site.

Figure 2: Ports meeting the assumed minimum hard criteria for large construction-phase uses, with assumed ideal sailing distance from those ports indicated⁴. Refer to Appendix C for full page versions.

Marshalling/assembly, 200km (108nm) zone highlighted



Fabrication/manufacturing, no sailing distance highlighted



There are currently no major ‘hub’ ports in Scotland providing co-located marshalling/assembly and fabrication/manufacturing on a scale comparable to the facilities that have been developed in the past 10 years of the offshore wind industry at ports in other North Sea countries. Examples of these include Rotterdam and Vlissingen (both Netherlands), Cuxhaven (Germany) and Esbjerg (Denmark).

Significant additional marshalling/assembly port capacity in Scotland is likely to be required in the form of sites with adequate laydown areas, quays to simultaneously accommodate multiple large transport and installation vessels and component transfers, and opportunities for development of floating storage moorings. This conclusion is based on a high-level assessment of demand using onshore laydown area as a representative port characteristic. The capacity gap is predicted to occur irrespective of whether fabrication of components occurs in Scotland or elsewhere.

Four of the ScotWind zones have three ports or fewer within an assumed ideal sailing distance of 200km (108nm) for marshalling/assembly, also taking into account other assumed hard criteria⁴. Based on recent examples including the largest projects in Scotland to date, a nominal 0.5-1GW offshore wind project requires two marshalling/assembly ports in parallel during construction – further emphasising that these ports have a high chance of use if the relevant zones are developed.

Finding 3: Suitability of current port development plans for offshore wind

A sample of port masterplans and development proposals for ten ports⁵ assessed to have significant potential for offshore wind use was reviewed. Several ports have existing development proposals that would provide additional technical capability and capacity to support offshore wind. The majority of development proposals are not solely targeted at the offshore wind sector.

Considering SOV based O&M use, individual proposals are broadly technically appropriate or in excess of what would be required for this use alone. The adequacy of development proposals to support fabrication/manufacturing and marshalling/assembly is mixed; some proposals contain quay lengths and laydown areas that risk restricting the methodologies available to offshore developers/contractors to a greater extent than is the case elsewhere in the UK and Europe.

The high-level demand assessment indicates that there is likely to be demand for larger and/or more facilities than those currently contained in the sample set of development proposals we have had sight of. This conclusion could be further substantiated by a more extensive review of port development proposals in dialogue with Scotland's ports.

Finding 4: Floating offshore wind and compatibility of facilities

Specialised infrastructure is likely to be required to support floating deployment, but requirements are more uncertain than for fixed-bottom due to the stage of development of the various competing technologies.

For semi-submersibles, this could include deeper water (20-25m) quays for floating assembly and large scale sheltered floating storage areas of similar depth or greater. No quays of this depth currently exist in the UK⁶. The Cromarty Firth and Orkney (Scapa Flow) stand out as having significant potential for semi-submersible assembly facilities, based on existing or potential technical capability and their central positions relative to the development zones.

For spars, methodology requirements for additional infrastructure appear more uncertain but could include ports with the same capability as for fixed-bottom technology, followed by use of sheltered water areas of 80-90m+ depth if vertical assembly processes are used. Alternatively, there may be a demand for quays or linear piers over 20-30m+ water for initial vertical formation of spar bases, followed by further vertical fabrication and ballasting alongside vessels or heavy-duty pontoons in 80-90m or greater water depths. Assuming these requirements, Loch Kishorn stands out as having the most significant potential.

We expect that facilities developed for the large port uses for fixed-bottom technology would also have capability and be in demand as part of the supply chain for floating. This is because the quantum of floating components in terms of mass and size is expected to be broadly similar or greater than for fixed-bottom. Specialised port infrastructure will be higher cost, which should incentivise the use of conventional port facilities wherever possible at intermediate stages in the supply chain.

⁵ As available in the public domain.

⁶ We note that a 2018 study for Scottish Government also considered similar quay depths in the context of oil and gas decommissioning, and recommended Dales Voe (Shetland) as a potential site [30].

Finding 5: The strategic decarbonisation case for port investment created by the net-zero targets

Scottish ports operate in a free market. As such, expansion/upgrade decisions are based on business confidence in future demand. The rapid rate of offshore wind market evolution, and hence emergence of certainty in demand, compared to the relatively long lead-time for port upgrades means that there is a risk of continual under-supply in suitable port capacity.

The rapid offshore wind build-out rate required to meet the net-zero targets⁷ is such that there may be a strategic decarbonisation case for taking port investment decisions sooner and at greater risk than has historically been the norm.

In addition, the long design-life of port infrastructure is such that any upgrades implemented now must be compatible with a future fully decarbonised lifecycle for offshore wind, including supply chain stages such as manufacturing, shipping and in-port component handling and assembly.

Finding 6: Suitable locations for expanding capacity for operations and maintenance (O&M), and development of potential hubs

We expect O&M activities to be developed at a wide range of ports due to the geographical distribution of existing capability and also the distributed nature of the future development zones.

We believe that ports with the greatest potential to serve as multi-project hubs include, but are not limited to; Montrose, Aberdeen, Peterhead, Scrabster, Kirkwall, Stromness and Lerwick. This assessment is based on position relative to the potential development zones, existing capability to support both SOV and CTV methodologies, potential for future development, and appropriateness of O&M use (i.e. it would not preclude larger offshore wind uses). Fraserburgh, Wick and Stornoway are similarly well geographically placed; Fraserburgh and Wick already support CTV based O&M. However, they would likely require more significant upgrades to support SOV based O&M.

Other ports may be suitable for supporting one class of O&M vessel only, or for use on individual projects. We also note that all port use on actual projects is subject to the decision-making processes of the organisations involved.

Finding 7: Suitable locations for expanding capacity for large construction phase uses, and development of potential hubs

Of the locations reviewed in this study, the Cromarty Firth and Inner Moray Firth, and Orkney and Caithness areas were found to be centrally located relative to the development zones. As such, they were assessed as being technically suitable to support multiple fixed-bottom and floating projects (particularly semi-submersible technology), providing long-term potential.

Aberdeenshire is geographically well located relative to the development zones and Aberdeen Harbour is already undergoing major expansion. However, further seaward expansion of the type and scale required for the offshore wind industry on the Aberdeenshire coast would be expected to be costly relative to the other options due to the topography. In addition, the greater water depths that may be required for floating component assembly are not available.

Further infrastructure development may be justified elsewhere but we consider that their viability will be more dependent on which areas are leased in the forthcoming ScotWind Leasing round; these include Stornoway/Arnish, Lerwick, Hunterston, and the ports in the Forth and Tay area. The latter may also find their business case strengthened by development of The Crown Estate Round 4 Dogger Bank Zone, with the same also true for ports in the North-East of England with respect to future Scottish offshore development.

Fabrication/manufacturing use of ports is noted to be product and business specific and significantly influenced by non-port factors, as well as existing or potential port capability.

⁷ We have assumed that a 2-3GW/year offshore wind build-out rate will be required in Scotland after 2025. This would enable Scotland to provide 50% of the 75-100GW of UK installed capacity estimated to be required as part of a net-zero energy system, based on the Committee on Climate Change Net Zero Technical Report [3] and Arup in-house analysis.

Recommendations

We make the following recommendations based on the above findings. The recommendations are targeted at CES and the other public sector project partners in accordance with the scope of the study.

Recommendation 1: Scotland should collectively aim to increase large port capacity that is suitable for marshalling and assembly activities, acting as a key enabling action for growth of domestic manufacturing

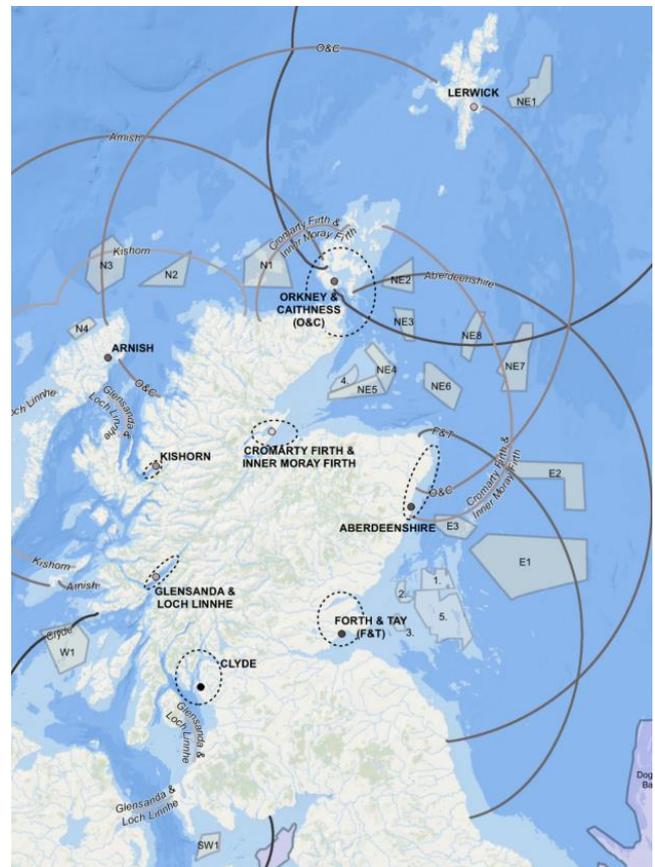
Development of large port capacity in Scotland that is well suited to the needs of the modern offshore wind sector for marshalling/assembly and manufacture/fabrication activities has been limited, both in terms of scale and number of locations. This contrasts with other North Sea countries such as the Netherlands, Germany and Denmark. This study has not explored the drivers for development of these facilities in other countries. Contributing factors are understood to include historically different models for port ownership, investment and industrial strategy, and in some but not all cases, early development of the manufacturing facilities that have acted as ‘anchor tenants’.

Irrespective of the reasons for any historic differences with other countries, the context for considering port development in Scotland now is radically different compared to three years ago. In that time the significant cost reductions offshore wind has achieved in the UK has become apparent via the Contracts for Difference (CfD) process, the importance of achieving net-zero has become more widely recognised, and the magnitude of offshore wind development required to achieve net-zero has become apparent.

Given this context, we recommend that public and private sectors collectively recognise that marshalling/assembly capacity should be prioritised, based on the following key factors;

- the build-out rate of offshore wind required to meet net-zero targets may not be achievable without significant expansion of marshalling/assembly port capacity. This risk needs to be considered against the counter-risks of over-developing of additional port capacity;
- development of offshore wind in Scotland at a competitive cost may not be achievable unless further marshalling/assembly capacity is developed. Recently completed or under development 0.5-1.0GW+ projects in Scotland and the rest of northern Europe have made extensive use of marshalling/assembly facilities;
- the expected continued build-out associated with offshore wind from the late-2020s onwards should provide a more consistent stream of work and employment than has been perceived in the past – this will enhance the overall value case; and
- marshalling/assembly should not be seen as a distinct opportunity to fabrication/manufacture. On recent projects we are aware that more on-site works than planned have typically taken place in marshalling/assembly ports indicating the potential for organic growth into more manufacturing functions. Prospective investors in fabrication/manufacturing facilities would logically be likely to favour locations with adequate port capability already available.

Figure 3: 200km (108nm) sailing distance perimeters from nine groupings of ports with marshalling/assembly potential. Refer to Appendix C for full page version.



The UK ports sector, including Scotland, currently operates in a free market with a limited role for the state. In this context, we recommend that the following ideas could be explored further;

- mechanisms for ports to be provided with long-term market confidence in offshore wind, and earlier certainty in individual offshore wind projects;
- mechanisms that encourage pooling of funds from multiple projects to support port infrastructure enhancements. This could have synergies with the existing industry collaboration clusters (Forth and Tay, and DeepWind), and could lead to the formation of more geographically localised ‘sub-clusters’ for industry collaboration. The recent shift from ~0.5-1GW projects to 3-4GW ‘pipeline projects’ under single developers may also assist this; and
- whether substantially different models of public and private collaboration are required in the ports sector. A key issue in the offshore wind context is the utility-like nature of ports, arising because O&M and marshalling/assembly port use is sensitive to distance and location, arguably more so than many traditional port uses.

We also note that there is significant international interest in the offshore wind and ports sectors around the idea of major hub ports where multiple manufacturing and marshalling functions are co-located. This study did not consider in detail the merits of such a facility compared to the alternative of a more distributed model across multiple ports. However, we do make the following observations;

- a major manufacturing hub would be most cost-effective if it had a large area of offshore wind development within its own marshalling/assembly catchment, everything else being equal. However, to achieve manufacturing economies of scale it would likely also need to ship components to marshalling/assembly ports elsewhere for non-local projects;
- a major manufacturing hub would be unlikely to produce all, or even the majority of components, required for an offshore windfarm due to the complexity and scale of projects. A modern nominal 1GW project may source foundation and turbine components alone from ten or more manufacturers;
- based on the ScotWind zones, future offshore wind development off the coast of Scotland is relatively well distributed. No single port in Scotland is within the assumed ideal 200km (108nm) sailing distance⁸ for marshalling/assembly of all ScotWind zones (see Figure 3). However, there are ports with significant potential for establishment of a hub that are within 300-350km (162-189nm) of 14 of the 16 ScotWind zones, ignoring the two more remote west coast zones⁹; and
- even if significant domestic manufacturing facilities are established, there will be competition from international manufacturing facilities, whose products developers and lead contractors may procure instead. A major hub facility would need to allow for multiple developers, manufacturers and contractors, who may be commercial rivals, to work in parallel on multiple manufacturing and marshalling/assembly functions.

Recommendation 2: Support strategic port planning for offshore wind

There may be inadequate time available for a ‘business-as-usual’ approach of allowing the market to iterate towards a system that provides appropriate additional capacity, given the net-zero targets. Conversely, there is also a risk for ports that they develop either excess or over-specified capacity compared to the industry’s needs.

This creates an argument for a more strategic approach to planning of port developments targeted at offshore wind. We recommend that any approach to strategic planning would require a partnership of public and private bodies from both the ports and offshore wind sectors.

We also believe there are smaller, readily achievable discrete activities that could be of value, such as;

- encouraging a focus across industry on taking actions that enhance long-term supply chain confidence. We note that the ScotWind Leasing process already contains requirements targeted at this;

⁸ See full report for more details.

⁹ W1 and SW1.

- further development and publication of demand projections, noting the high-level nature and uncertainties associated with those published in this study;
- cross-industry involvement in the generation of a standardised, concise set of guidance for the ports industry on infrastructure requirements for offshore wind, including more certain requirements versus unknowns in relation to floating wind. Various sets of port requirements already exist in industry reports in the public domain and port requirements are discussed in outline in this study. However, further clarity may be beneficial in the industry to ensure appropriate and efficient upgrade proposals are developed and to provide further market confidence; and
- greater standardisation of forms of contract and leases between port operators and their offshore wind customers (i.e. developers and contractors), to help reduce contract formation costs and maximise time available for infrastructure improvements.

Recommendation 3: Encourage development of optimal O&M facilities

The study has identified that there are existing facilities that are adequate for both CTV and SOV based O&M. However, these facilities are dispersed, and the optimum facilities are likely to require additional capacity. The industry collectively should consider;

- development of additional capacity at the likely hub locations where multiple projects could be based. Multi-project O&M hubs may be more beneficial in rapidly developing a skills base and lowering costs. There would be a role for both the public and private sectors in promotion of hub locations. O&M is an area of relative UK strength in offshore wind, and as the industry continues to develop in Scotland this can be further built-upon;
- development of shared O&M facilities and infrastructure. Ports and harbours suited to O&M are typically in historic town-based locations with relatively constrained expansion potential. Shared facilities, such as office buildings, warehousing and berthing, could maximise available land and water space, and reduce the risks associated with individual offshore wind projects developing bespoke facilities in time for project completion; and
- whether smaller, remote harbours including those on islands, that could be used as O&M bases for individual projects should be supported. These locations may require more proactive promotion from outside parties, whether public or private sector, if they are to be used. Remote harbours could offer different benefits to more established harbours and potential hub locations, such as enhanced local community support for offshore wind and achievement of different social and economic objectives.

List of abbreviations

Abbreviation	Term
CCS	Carbon Capture and Storage
CD	Chart Datum
CES	Crown Estate Scotland
CTV	Crew Transfer Vessel
HIE	Highlands and Islands Enterprise
HGV	Heavy goods vehicle
HLV	Heavy Lift Vessel
O&M	Operations and maintenance
SE	Scottish Enterprise
SMP	Draft Sectoral Marine Plan for Offshore Wind [1] [2] (See also, Definitions)
SPMT	Self-propelled modular transporter
SOV	Service Operation Vessel
TCE	The Crown Estate (for England, Wales and Northern Ireland)

1. Introduction

1.1 Project background

Crown Estate Scotland (CES) recognises the need to support Scotland's ambitions to deliver large-scale offshore wind deployment as a key part of its net-zero future [3]. In the area of port infrastructure provision, current and emerging offshore wind market demand as well as technology development are driving a requirement to consider how port infrastructure in Scotland can play a part in supporting Scotland's offshore wind opportunities.

CES commissioned Arup to undertake a review of the suitability of port facilities in Scotland to support future offshore wind development. The study comprised a review of likely port requirements for the offshore wind industry up to 2040; cataloguing of existing port capabilities in Scotland; analysis of port locations relative to future offshore development zones; assessment of existing capabilities against industry requirements; and identification of opportunities to positively influence port infrastructure provision.

1.2 Purpose

This report provides a summary of the study. Its purpose is to provide;

- a summary of the assessment of the capability of the ports sector to support the offshore wind industry to 2040, at a strategic Scotland-wide level;
- identification of challenges and opportunities for port infrastructure provision in Scotland, to contribute to the decision-making processes of parties across the industry; and
- recommendations for consideration by CES and the wider public sector specifically. It was not an objective of the study to provide recommendations for consideration by private sector parties in the ports and offshore wind sector. Nonetheless, findings will be relevant to them.

1.3 Methodology overview

A baseline review of port use and requirements for offshore wind was undertaken. The review considered recent major projects and possible future technology evolution, and took account of major components, logistics methodologies, and vessels drawing on examples from the UK and continental Europe. Three main port uses in support of offshore wind were considered; operations and maintenance (O&M), and the construction phase uses of marshalling/assembly and fabrication/manufacture. The characteristics of these port uses are described in section 2. For the construction phase uses, the study focussed on foundation and turbine components on the basis that these typically drive the largest share of port use on a project. Fixed-bottom and floating offshore wind technologies were considered. The baseline review provided the basis for assessment of the capability of ports.

All existing ports and harbours in Scotland of potential significance for offshore wind were considered (Figure 4). A screening approach was used to focus data collection, and a mix of quantitative and qualitative assessment identified the ports with a minimum required level of suitability for each offshore wind use, as well as those ports most likely to be suited to supporting future development of multiple future offshore wind projects. A range of port attributes were characterised, including existing technical capability, potential for upgrade and proximity to offshore development zones. High-level projections for onshore laydown area demand, identified as a critical variable, were generated to inform the assessment.

The study was undertaken as a desk-based exercise utilising data from the public domain, CES and from Scottish public sector bodies. Data was collected on a like-with-like basis wherever possible. Workshops were held with CES, Scottish Enterprise (SE), Highlands and Islands Enterprise (HIE) and Transport Scotland (TS)¹⁰ to develop an understanding of their roles and interactions with the ports and offshore wind sectors, and relevant previous and

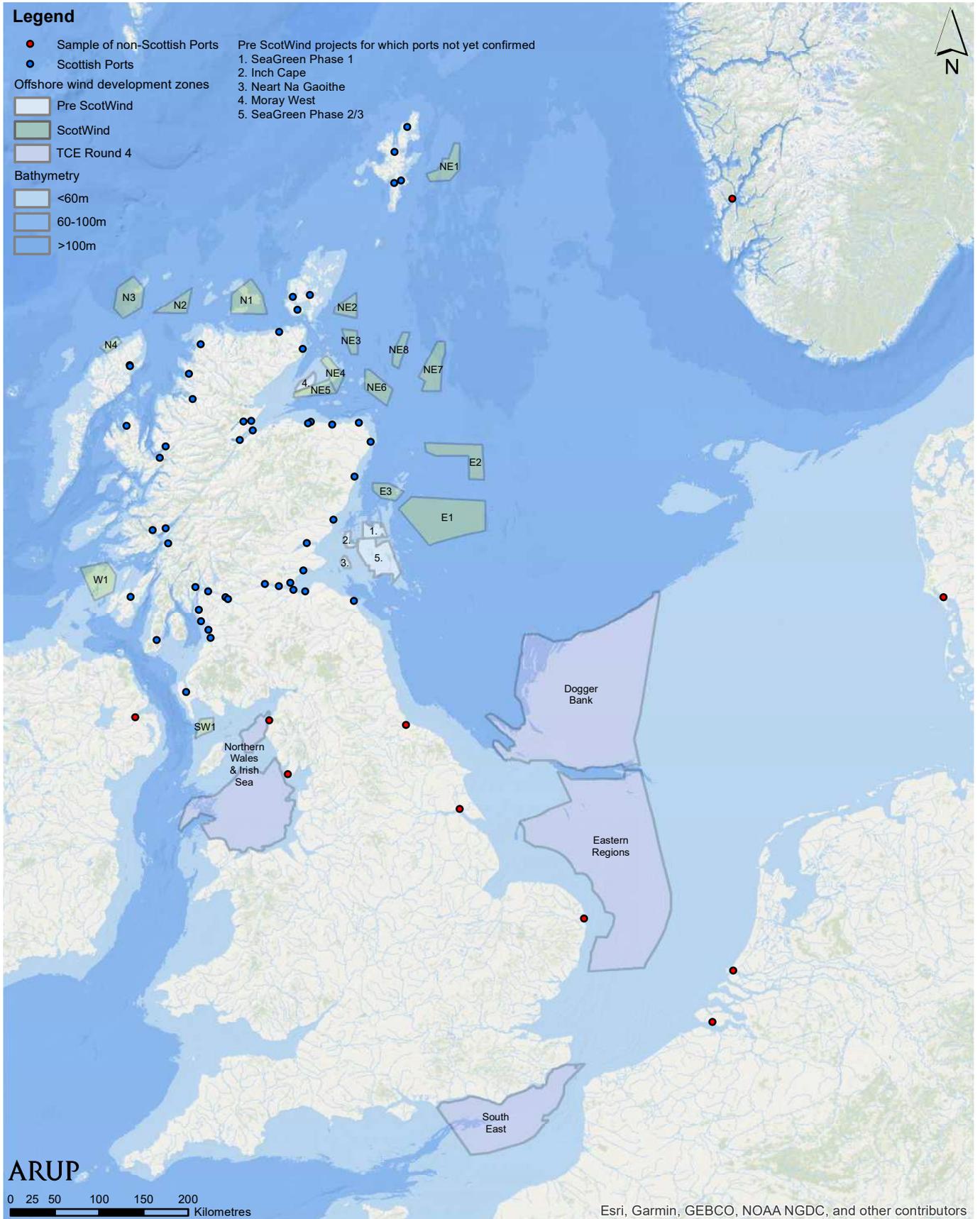
¹⁰ Arup was tasked with writing the report with input from Crown Estate Scotland, who commissioned the work. The report does not necessarily reflect the views of the other parties mentioned.

current initiatives¹¹. Engagement with other third parties including the ports, offshore wind developers, investors, contractors and the wider supply chain was not within the scope of this study. It is recognised that this could be the key next step in further progression of the findings and recommendations presented in this study.

The study was conducted considering technical and operational criteria only. Economic and social factors were not quantitatively considered. We also note that fabrication/manufacturing use of ports is particularly dependent on non-port factors.

¹¹ Such as involvement in references [4]-[6].
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Figure 4: Locations of future UK offshore wind development zones¹¹, the 50 Scottish ports considered in the main analysis in this study, and sample of 11 ports beyond Scotland used for comparison of distance characteristics to development zones.



¹¹ For further background on ports and offshore wind development zones considered in this study, see section 4.

2. What is an offshore wind port?

Key points:

- **The distinguishing features** of ports used for offshore wind are summarised in this section.
- For the purposes of this study, **the following port uses for offshore wind were considered:**
 - Operations and maintenance (O&M) port, with two main sub-distinctions:
 - Crew Transfer Vessel (CTV) based
 - Service Operations Vessel (SOV) based
 - Marshalling and/or assembly port
 - Fabrication and/or manufacturing port

These four uses are broad categories and are intended to capture the typical previous and reasonably foreseeable logistics approaches of offshore wind projects.

- A port supporting **multiple marshalling/assembly and fabrication/manufacturing functions** is commonly referred to as an Integrated Manufacturing Port/Hub or a Co-located Manufacturing Port/Hub. There are currently no significant UK examples of such a facility, but they already exist in and are under development elsewhere in Europe and beyond.

2.1 Introduction

The key characteristics that a port must typically have to fulfil offshore wind port functions are summarised in this section. Requirements are summarised for a nominal 1GW fixed-bottom project. This is the approximate scale of major projects recently constructed and currently under construction and provides a useful ‘unit-size’ for assessment purposes. Some UK projects due for completion in the mid-2020s are taking the form of ‘pipeline projects’ of around 2-4GW each.

The port requirements described are not prescriptive and are provided to aid general understanding; the division of functions between ports and distinctions can vary between projects. The minimum hard criteria and ideal criteria that were assumed for the assessment stages of the study are outlined in Appendix A.

2.2 Operations and maintenance (O&M) port - Crew Transfer Vessel (CTV) based

An O&M Port is used to host activities associated with the ongoing reasonably foreseeable operation and maintenance activities associated with an offshore windfarm during its design life.

The facilities established by a windfarm developer or future project operator at an O&M port are specific to the O&M strategy of the individual project (for example with respect to vessel choice). Typical facilities can include dedicated or shared berthing facilities for the O&M vessels with utilities and craneage, and an onshore facility containing office space for operations staff, a marine control centre for directing activities, terminal facilities for turbine technicians (e.g. changing, welfare and briefing facilities), and a small immediate spares warehouse. The same port and facilities, or similar temporary facilities, can be used for monitoring and support activities during the construction phase of a windfarm.

Typically, northern European projects to date have adopted a CTV based O&M strategy, whereby the vessels and technicians only stay at sea for a single shift. Due to their relatively small size, CTVs are well suited to utilising historic ports and harbours that may have experienced declines in their traditional industries.

O&M facilities have typically been developed on a single offshore wind project basis due to the nature of the public financial support regimes and contractual arrangements within projects. Consolidation of O&M bases and sharing of functions where there is a common operator (typically the major energy company who was the original lead developer), is beginning to emerge [7].

The typical primary requirements for CTV based O&M port facilities for a nominal 1GW fixed-bottom project include;

- 0.75-1.50ha onshore area for development of the onshore facilities (assuming new build), ideally adjacent to the berthing;
- 1-2ha of sheltered water area for vessel berthing, in the case of CTVs typically heavy-duty pontoon-based berthing for 15-30m long vessels and 3m minimum water depth; and
- no or minimal vessel access restrictions (e.g. tidal windows, locks, gates, opening bridges).

Major maintenance due to unexpected events, such as replacement of a major component like a blade, would require a port accessible to larger vessels, as described for marshalling/assembly and fabrication/manufacturing below.

Ports suitable for CTV based O&M will generally be capable of supporting construction phase ancillary services, such as pre-construction survey campaigns and construction management.

Figure 5: Crew Transfer Vessels (CTVs)



2.3 Operations and maintenance port - Service Operations Vessel (SOV) based

SOVs are larger vessels than CTVs that can fulfil a wider range of functions and are capable of operating offshore for weeks rather than a single day. SOV based O&M strategies have been used on a smaller number of projects to date but are more likely to be used for future projects due to the greater distance range of the vessels and possibilities for efficiency savings, both in terms of O&M and infrastructure on each turbine foundation.

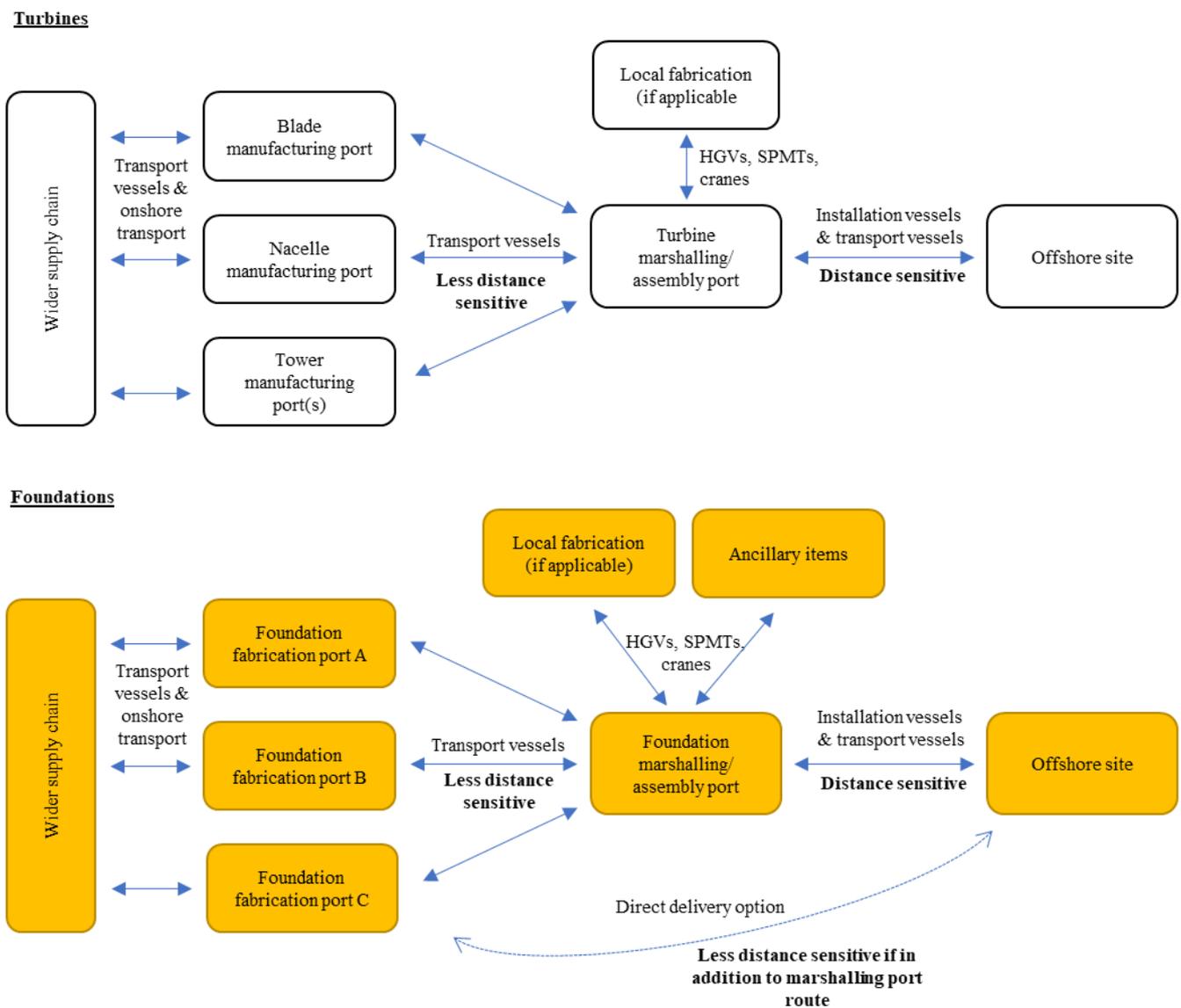
Compared to ports for CTV based strategies, SOV based O&M ports would typically require deeper and longer berths for the larger vessels (see Appendix B), are better able to share berthing with other port users and tolerate vessel access restrictions (as vessels return to port less frequently) and may require fewer onshore facilities as some functions can be located on the SOVs (such as marine control and technician welfare). It is also feasible for projects to adopt mixed CTV and SOV based O&M strategies.

Helicopter access can form part of O&M strategies, particularly with increasing distance of windfarms from shore. Helicopter facilities were not considered in this study.

2.4 Marshalling and assembly

A marshalling or assembly port is used as an intermediate facility during the construction phase of a windfarm. A marshalling or assembly port would be located relatively close to the offshore construction site and very likely closer than most of the project’s fabrication or manufacturing ports. They are used as temporary storage or assembly locations for major components (such as foundation and turbine components) originating from different locations of original manufacture, before final collection for installation at the offshore site. Figure 6 illustrates the key concept role of marshalling/assembly ports relative to fabrication/manufacturing in an offshore wind construction process for the major turbine and foundation components.

Figure 6: Schematic illustration of ports in a typical offshore wind supply chain for the major turbine and foundation components. It is feasible for individual ports to fulfil multiple roles. Note that there is no standard model, and that all logistics processes are subject to the design and contractual arrangements of individual projects.



+ **Port-based supply chains for other components** (e.g. offshore substation, export cables, inter-array cables, scour protection)

Marshalling and assembly ports are characterised by flexibility and relative proximity to the offshore site. Their inherent purpose is to de-risk the logistical processes of a project and to not act as a constraint on offshore activities. For example, they would typically require quays with relatively unconstrained water depths and minimal

tidal restrictions for the project’s major transport and installation vessels, minimal air draft (clearance) constraints and large open onshore laydown areas and sheltered water areas for activities including storage of components, inspections, final minor works and assembly. The need for a defined location for handovers of contractual responsibility for components can also contribute towards the case for a marshalling/assembly port.

Projects may make use of multiple marshalling and assembly ports, for example one each for foundations and turbines. Not all projects make use of marshalling and assembly ports that are distinct from the original fabrication and manufacturing ports.

Port requirements can be broadly considered as onshore requirements and vessel access requirements. The former may typically be driven by the component and logistics process design of an individual project. The latter is also driven by the desire for ports to not act as a constraint on the competitive tender processes for project services that are dependent on the major transport and installation vessels, of which there are a limited number operating in northern Europe.

The typical primary requirements for marshalling/assembly port facilities for a single function (e.g. either foundations or turbines) for a nominal 1GW fixed-bottom project include;

- onshore area for storage and marshalling of components, comprising an area of 4-8ha as an absolute minimum to partially fulfil requirements but ideally around 10-20ha. The size of area required is dependent on the logistics processes of a project. Storage areas must also have adequate load capacity for the components and sufficient access routes to the quays;
- quays for simultaneous berthing of two major component transport and/or installation vessels, each of length 140-240m and requiring 6-12m water depth or greater;
- entrance width suitable for relatively wide beam installation vessels, ideally 50-60m or greater;
- sheltered water areas and suitable quays or moorings for ‘floating storage’ of components for shorter time periods on vessels or on barges, or in the case of floating foundations in self-floating storage;
- no or minimal vessel access restrictions that would prevent high-cost installation vessels having 24-hour access (e.g. tidal windows for shallower entrance channels or berths, locks, gates, overhead lines, opening bridges); and
- proximity to the offshore site or ‘distance sensitivity’. This key variable is discussed further in section 3.

Figure 7: Components in a fabrication port (L) and marshalling port (R)



2.5 Fabrication and manufacturing

Fabrication and/or manufacturing ports would ideally have similar capability in terms of maritime infrastructure as marshalling and assembly ports, such that they can also fulfil that function for nearby offshore wind projects.

However, minimum capability requirements can be lower. On projects also using marshalling/assembly ports there is less need for operational flexibility, berths do not necessarily need to be accessible by installation vessels, and constraints such as delays for tidal windows and berth availability are more acceptable.

The typical primary requirements for fabrication and manufacturing port facilities for a single function (e.g. tower manufacturing) for a nominal 1GW fixed-bottom project include;

- 4-12ha+ onshore area for fabrication and storage of components, which may include relevant indoor/covered facilities, of sufficient load capacity and with sufficient access to the quay;
- quay for berthing at least one major component transport and/or installation vessel, of length 140-240m and requiring 6-12m water depth. However, there are successful fabrication/manufacturing facilities which are only accessible by even shallower draft vessels and barges – this is viable in an overall port system where there are other ports providing marshalling/assembly functions which are accessible by installation vessels.

2.6 Integrated Manufacturing Ports / Co-Located Manufacturing Ports

A port supporting multiple marshalling/assembly and fabrication/manufacturing functions are commonly referred to as an Integrated Manufacturing Port/Hub or a Co-located Manufacturing Port/Hub. There are currently no significant UK examples of such a facility, but they already exist and are under development elsewhere in Europe and globally, such as at Esbjerg (Denmark), Cuxhaven (Germany) and Rotterdam (Netherlands). The rationale for such facilities may be linked to the ‘clustering benefits’ for workforce and supply chain, as well greater efficiencies from sharing high-cost infrastructure.

This study did not consider in detail the merits of such a facility compared to the alternative of a more distributed model across multiple ports.

The technical requirements for a multi-function and multi-user facility can be considered based on scaling and combining the variables described for marshalling/assembly and fabrication/manufacturing above, subject to additional considerations such as;

- the extent to which the demand peaks and troughs from multiple users can be managed to make most efficient use of shared infrastructure, for example for quay access or onshore laydown area; and
- mechanisms for sharing the site and essential infrastructure between different users who are potentially industry rivals.

3. Assumed capability requirements

Key points:

- **Capability requirements** were defined by review of databases of components and vessels used on past projects and examples of port use in practice on recent major projects. Projections for future technology were based on Arup in-house concept sizing tools which are based on a combination of past technology extrapolation and engineering design principles.
- **Distance sensitivity.** Offshore wind port use for marshalling/assembly port use, CTV based O&M port use, and to a lesser extent SOV based O&M, is sensitive to the distance to the offshore windfarm. This is a key differentiating feature of port use for offshore wind.
- **Net-zero supply chain.** The offshore wind supply chain including activities in ports must become net-zero by the 2040s and have made major progress towards this goal by 2030. Given the long design life of port infrastructure, decisions made now regarding future port development and upgrades will influence whether this can be achieved. Port infrastructure investments made now must be compatible with a future fully decarbonised supply chain.

3.1 Assumed requirements for vessels and components

The port capability requirements assumed for this study were defined by a baseline review encompassing current offshore technology, methodologies, vessels and port use on past projects and projections for future evolution.

To identify trends in major component sizes and vessels Arup in-house databases of past projects and concept sizing tools were used. The following major component and vessel types were considered in the review. This list was selected in order to provide an envelope of dimensions and masses for definition of the port requirements used for the study; other categories not explicitly considered are expected to fall within or close to the envelope:

- Vessels:
 - O&M: CTVs, SOVs.
 - Transport and installation: coastal and sea going barges, general cargo vessels, jack-up installation vessels, heavy-lift vessels, semi-submersible vessels.
- Components: turbines, monopiles, jackets, semi-submersibles, spars.

Reference sizes for the major components and vessels that ports in Scotland might be reasonably expected to accommodate are summarised in Appendix B. The components considered were used as a representative sample for the purposes of this study. Other foundation types not explicitly considered, such as suction-bucket jackets and floating tension leg platforms are not expected to result in significantly different port requirements outside the envelope of those considered.

Due to the uncertainties involved, no projections were generated for turbine capacities greater than 20MW.

Figure 8: Offshore installation



3.2 Distance sensitivity of ports to windfarms

Port use for offshore wind marshalling/assembly and O&M is sensitive to the distance to the offshore site. This is a distinguishing feature of offshore wind use of ports compared to general port-to-port shipping. This has the potential to create utility-like limited-choice relationships between individual ports and offshore windfarms.

3.2.1 Marshalling and assembly ports - distance sensitivity

Distance sensitivity arises in the construction phase of offshore wind projects due to time-sensitive offshore installation costs and demanding project milestones associated with public financial support regimes, consenting, and the commercial need to start selling power. The potential cost of delays in installation are typically very high relative to a project's port costs. For example, the offshore installation costs associated with a project (e.g. associated with vessels charter and offshore construction processes) may typically number in the hundreds of millions of pounds, with high daily costs for specialised installation vessels and personnel, whereas direct port-related costs (e.g. port charges and fees, minor infrastructure upgrades, establishment of temporary facilities, in-port handling costs) may typically be millions or tens of millions of pounds for a project.

This difference creates a commercial rationale for the use of local marshalling/assembly ports holding significant buffers of components to isolate the offshore construction programme from transportation and widely geographically distributed upstream supply chains. The two largest projects developed in Scotland to date, Beatrice and Moray East have both made use of ports for marshalling/assembly functions, with Nigg and Invergordon used in both cases. Other recent major UK projects have similarly made use of marshalling/assembly ports. In most cases they have used two separate major facilities, one each for foundations and turbines (Table 1).

Table 1: Use of marshalling and assembly ports by major recent Scottish and other UK projects (references [8]-[15]).

Project	Offshore construction	Rated capacity	Foundation marshalling / assembly port?	Turbine marshalling / assembly port?
Beatrice	2017-2019	0.59 GW	Yes	Yes
Moray East	2019+	0.95 GW	Yes	Yes
Walney Extension	2017-2018	0.69GW	Yes, same port for foundation and turbine marshalling/assembly	
East Anglia One	2017-2020	0.71 GW	Yes	Yes
Hornsea One	2018-2019	1.20 GW	Yes	Yes, co-located with blade manufacture
Triton Knoll	2020+	0.86 GW	Yes, co-located with monopile fabrication	Yes

3.2.2 Floating offshore wind - distance sensitivity

There is greater uncertainty regarding the extent to which large-scale floating offshore wind deployment will be sensitive to the distance from the marshalling/assembly ports to the offshore site.

Use of lower-cost installation vessels in some prospective methodologies for large-scale floating deployment, for example tow-out of fully assembled turbines with tugs or anchor handling vessels, may reduce the costs associated with delay risk. This in turn may act to reduce the distance sensitivity of marshalling/assembly ports for floating deployment. However, other factors such as weather risk will remain and in their transit state turbines may be more vulnerable than once fully ballasted and secured on their permanent station.

3.2.3 O&M ports - distance sensitivity

In the O&M phase, distance sensitivity arises due to what are currently relatively labour-intensive methods for personnel working in an extreme environment with associated need for robust safety procedures and limited daily working windows. As such, every minute of an offshore technician's time is of sufficient value to justify distance to site as a major priority in selection of an O&M port.

Due to the nature of daily servicing, CTV-based O&M ports are highly distance sensitive with 2-3hours sailing time often the maximum considered acceptable to the offshore site. SOV based O&M ports are inherently less sensitive to distance; however, there is still an intrinsic advantage to a location close to the offshore site for efficiency of resupply of personnel and equipment and for mitigation of operational risks.

3.3 Net-zero supply chain

Major port infrastructure upgrades typically have a lifespan in excess of 50 years. Therefore, any investments in ports for the offshore wind industry in Scotland should be made such that they are consistent with Scotland's 2045 net-zero target, and the 2030 interim target of 70% greenhouse gas emissions reduction. This will influence the targeting of any port investments by third parties both in terms of location and type. Factors influencing greenhouse gas emissions associated with ports and key opportunities are highlighted in Table 2.

Table 2: Summary of key influencing factors and opportunities in relation to ensuring any new port infrastructure is net-zero compatible.

Emissions source – broad category	Key influencing factors	Opportunities
Fixed port infrastructure and equipment	<ul style="list-style-type: none"> • ‘Capital carbon’ associated with maritime structures, onshore port buildings and infrastructure. • Scale of development, design life, materials. 	<ul style="list-style-type: none"> • Prevent unnecessary duplication of functions across multiple ports. • Develop multi-use, flexible infrastructure likely to be suitable for unknown future developments in offshore wind and other industries. • Do not speculatively overdevelop infrastructure, but do consider how future expansion would be achieved
Mobile port plant and equipment	<ul style="list-style-type: none"> • Plant and equipment fuel sources. • Availability of local renewable generation for electrification of plant and equipment, or generation of near zero-carbon fuels. 	<ul style="list-style-type: none"> • Increasing electrification of vehicles in wider industry. • Vehicles operating within known limits such as a port are good candidates for electrification, or near zero-carbon fuels such as renewably produced hydrogen.
Onshore transport emissions influenced by ports	<ul style="list-style-type: none"> • Port workforce and offshore wind personnel travel. • Supply chain via road. • Supply chain via rail. 	<ul style="list-style-type: none"> • Ensure access to ports is considered as part of the wider changes to transport systems that are necessary for emission reduction (e.g. active travel and public transport enhancements, zero-carbon fuel for freight). • Port functions in the construction phase of offshore wind in particular can attract large numbers of personnel from across the supply chain on short-duration visits. Use of ports readily accessible by land-based travel rather than air travel would minimise this emissions source.
Vessel transport emissions influenced by ports	<ul style="list-style-type: none"> • Supply chain via sea. • Provision for electrical power supply to vessels in port (‘cold-ironing’). • Provision for lower carbon vessel fuel (e.g. LNG). • Provision for near zero-carbon vessel fuel (e.g. ‘green hydrogen’ generated with renewable electricity). 	<ul style="list-style-type: none"> • Bespoke O&M vessels operating from known ports are strong candidates for use of zero-carbon vessel fuel prior to wider adoption in shipping. • Assuming a stable pipeline of development projects, the same should be true of installation vessels operating exclusively across the North Sea and Baltic Sea market.
Port-based manufacturing and assembly emissions	<ul style="list-style-type: none"> • Capital carbon of offshore wind components. • Availability of local renewable energy generation. 	<ul style="list-style-type: none"> • Emissions associated with production of some offshore components, particularly foundations, have effectively been ‘offshored’ beyond Europe on recent projects. • Effective carbon pricing or taxation of imports should encourage manufacturing closer to windfarm sites.

4. Port capability and positioning

Key points:

- **A numerically based screening and multi-criteria assessment exercise supplemented with qualitative assessment was carried out** to identify ports with significant existing capability or potential for offshore wind use for multiple future projects. As part of this assessment individual port physical characteristics, distance characteristics (proximity to offshore development zones) and geographic characteristics (such as population and transport links) were considered.
- **Localised groups of ports with high potential.** The analysis highlighted geographically-close groups of ports with particularly high potential for offshore wind use.
- **Market concentration.** CTV based O&M and marshalling/assembly port uses are particularly sensitive to distance to the offshore zone. The dispersed nature of Scotland's ports and future windfarm zones means that situations of limited choice could arise for ports and windfarms relative to one another. However, these would not be 'no-choice' situations, as alternative methodologies could be developed.
- **Development proposals.** Many ports have existing infrastructure development proposals that if realised would provide additional technical capability and capacity suitable for offshore wind. Most proposals are not solely targeted at offshore wind. Based on a limited review of such proposals (contact with ports was out with the scope of the study) we observe;
 - many proposals would be well suited to SOV based O&M activities, or to small- to medium-scale marshalling/assembly or fabrication/manufacturing;
 - some proposals whilst referencing offshore wind, lack clear definition of which specific functions they are targeted at within the documents that are in the public domain;
 - the scale of proposed additional capacity contained within the proposals that would be suitable for offshore wind marshalling/assembly may be below the potential demand when Scotland is considered as a whole;
 - future phases of expansion should be considered in the design of port upgrades and expansions that are targeted at offshore wind; and
 - considering the Scotland-wide strategic perspective, fewer but more ambitious port infrastructure developments may be better suited to supporting offshore wind development, and hence be more advantageous in minimising project costs, maximising deployment rates and creating local economic opportunities. However, most existing development proposals are not solely targeted at offshore wind.
- **Capability for O&M.** There is broadly adequate technical capability in appropriate locations relative to development zones, but we expect capacity to be constrained due to existing uses. As such, expansion of both berthing and onshore area capacity suitable for O&M may be justifiable in multiple locations. Potential locations for long-term multi-project hubs should have capability to support both CTV and SOV-based service models.
- **Capability for 'large' functions.** There are limited ports in Scotland with adequate existing capability to support the 'large' offshore wind port functions of marshalling/assembly and fabrication/manufacturing. Given the expected increase in demand (see section 6), there is likely to be an opportunity to develop additional large port capacity in Scotland. This would help ensure that the same methodologies and contracting arrangements as used for recent major projects, in Scotland and elsewhere, can continue to be used to support an increasing offshore wind build-out rate.

4.1 Capability and positioning assessment methodology

4.1.1 Objectives

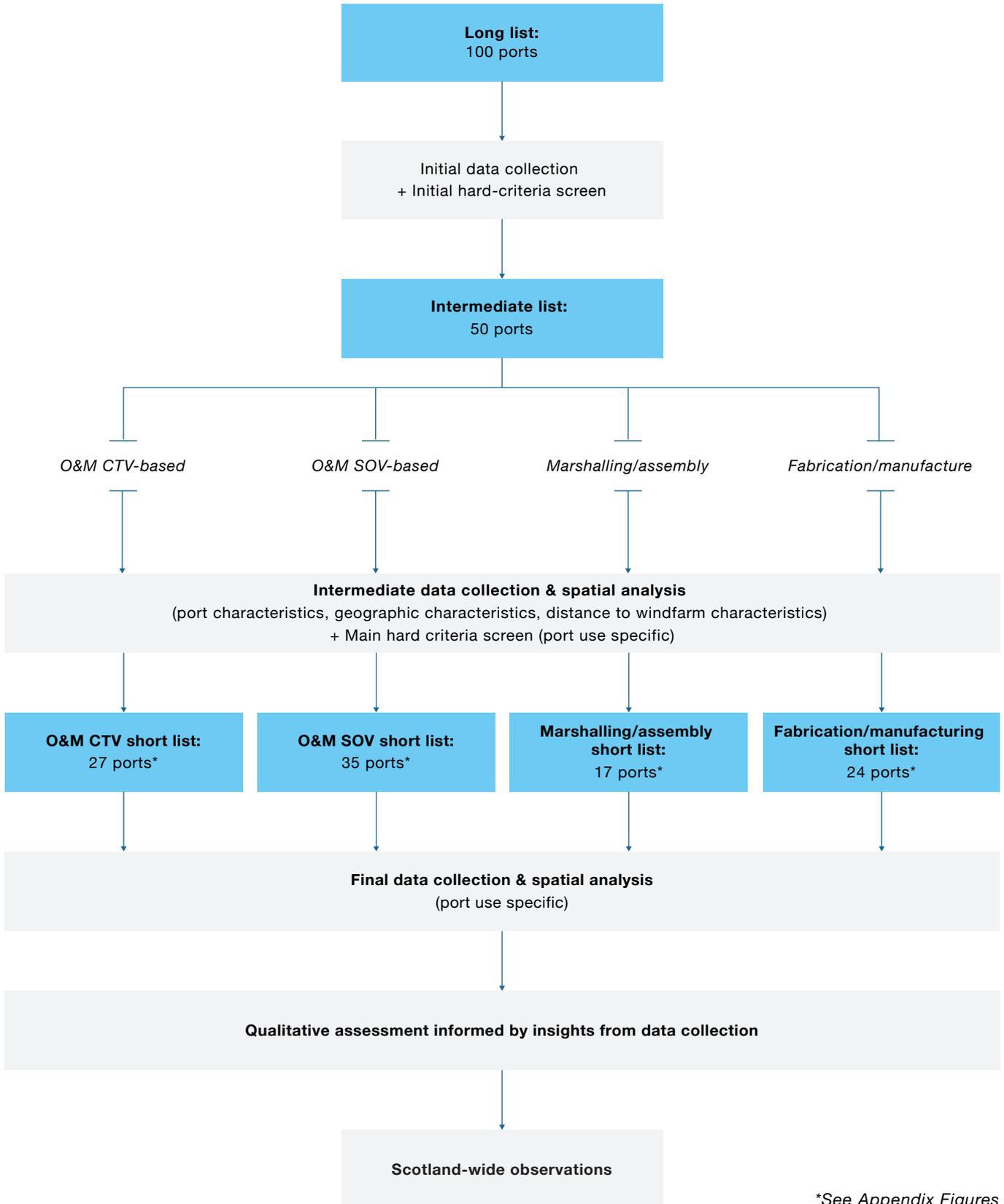
Numerically-based screening and multi-criteria assessment of ports in conjunction with qualitative assessment was carried out. The purpose of this exercise was to identify ports with significant existing capability or potential for offshore wind use for multiple future projects. The objective of this exercise was to allow Scotland-wide observations and recommendations to be made.

The objective of the exercise was however not to form detailed port-specific conclusions. All observations relating to individual ports in this report are made to assist the overall purpose of the study outlined above, and should not be used by any party for decision making purposes without further study. Where individual ports are not mentioned, it does not mean that port could not be used on an offshore wind project. The use of a port for offshore wind functions is always the result of the individual requirements of developers or contractors and the agreement of mutually acceptable terms with a port. Similarly, investment decisions in new infrastructure or upgrades by any party, private or public, consider the specific merits of individual cases, which this study did not consider in detail.

4.1.2 Overview of process

The process is summarised in Figure 9. Successive rounds of screening with minimum hard criteria specific to the four port uses were used to focus analysis. The hard criteria adopted are summarised in Appendix B.

Figure 9: Process for port capability and positioning assessment.

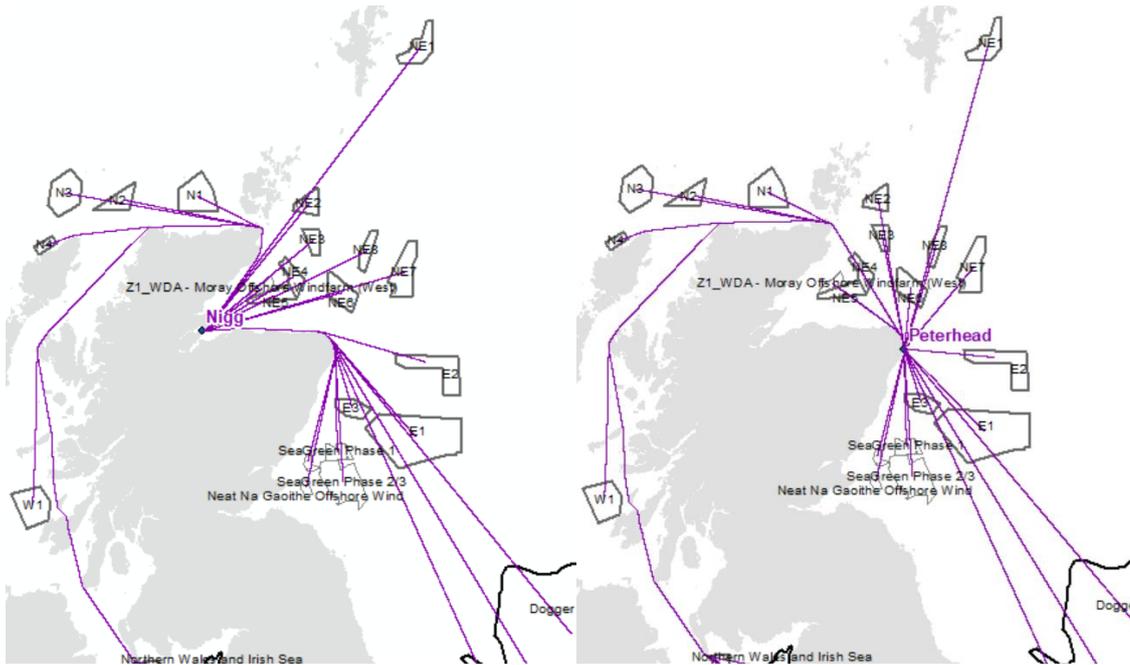


*See Appendix Figures

Data was collected on port characteristics in three categories:

- Distance characteristics, relating to sailing distances calculated between ports and offshore zones. Sailing distances were calculated as simple straight lines avoiding the coastline at a 200m offset, so should be considered minimum distances. Examples are illustrated in Figure 10.
- Geographic characteristics, relating to the characteristics of a port’s local area including population, transport links and supply chain.
- Port characteristics, relating to the physical features and characteristics of a port and its infrastructure.

Figure 10: Sailing distance calculation examples, for Nigg (L) and Peterhead (R).



The decision of what data was collected was defined by the baseline review of port functionality requirements and an assessment of the available data on ports. Data was collected from sources available in the public-domain and from sources made available by the public sector project partners. Wherever possible data was collected from consistent sources to ensure ‘like-with-like’ comparisons were made. As previously noted, no direct consultation with port operators was undertaken. Characteristics for which data could not be fairly compared or comprehensively collected were not considered in the assessment, for example quay load capacity.

A weighted multi-criteria assessment exercise was then undertaken for each offshore wind port function, with 30-35 variables in each case. This considered both ‘minimum’ and ‘ideal’ requirements. For example, with respect to vessels sizes to be accommodated (see Appendix B).

Different weighting was used for each port function to reflect our judgement of differing levels of importance for different variables. For example, distance relationships to windfarms were prioritised higher for CTV-based O&M and marshalling/assembly functions than for fabrication/manufacturing. The methodology was designed to highlight the ports with the greatest potential for use for multiple-projects and those with existing capability or upgrade potential within reason. The weighting used was reviewed in conjunction with CES and the public sector project participants and sensitivity tests undertaken. These tests found that the overall results were relatively insensitive to weighting changes. Weighted multi-criteria assessment unavoidably contains subjectivity and has other limitations; therefore, the results were used as an informative intermediate tool and do not form the ‘final answer’ of this study.

Failure of a port to meet a hard criterion does not mean that port would not be used on specific individual offshore wind projects.

The development zones considered in the analysis were;

- pre-ScotWind Scottish windfarms under development without preferred ports announced as of November 2019 (referred to in this report as the ‘pre-ScotWind zones’);
- the Draft Plan Areas of the draft Sectoral Marine Plan for Offshore Wind for Scotland, that once finalised are expected to be available for lease bids as part of the CES ScotWind Leasing process (referred to in this report as the ‘ScotWind zones’) [1][2][16]; and
- rest-of-UK Seabed Bidding Zones that will be available for lease bids as part of The Crown Estate (TCE) Round 4 process [17], (referred to in this report as the ‘Round 4 zones’).

All future offshore wind development to 2040 was assumed to be in the above zones for the purposes of the analysis carried out in this study. Later in the 2020-2040 period, additional development zones may be required subject to the viability of the currently identified zones¹³. Non-UK future offshore development was not considered in the analysis; this could act as a source of additional demand for Scottish ports hosting fabrication/manufacturing facilities.

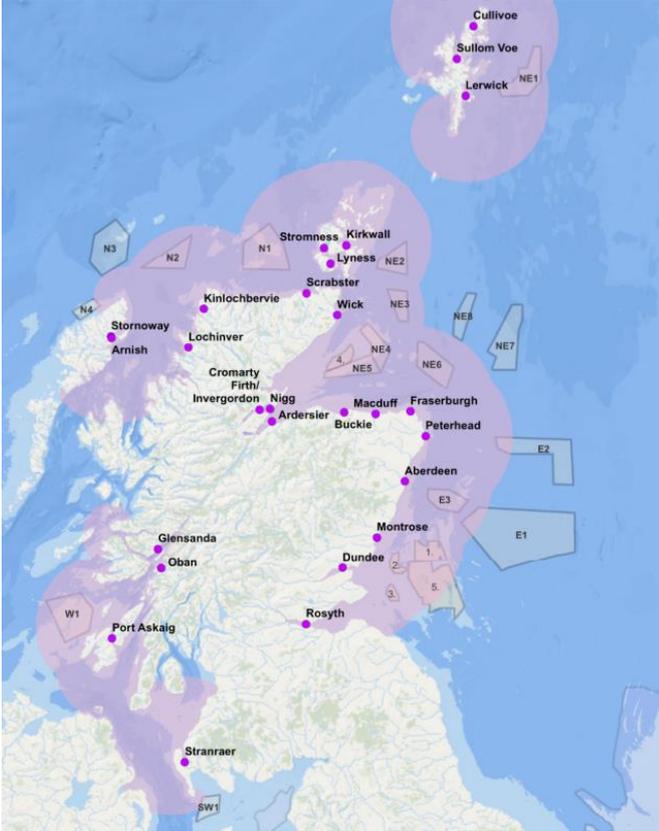
4.2 Ports meeting assumed hard criteria

Figure 11 summarises the ports that passed the assumed hard criteria. For the port functions considered to have significant distance sensitivity, the figures show the ‘catchment’ available within an estimated ideal sailing distance of the relevant ports. This is provided as informative context and is not a hard boundary.

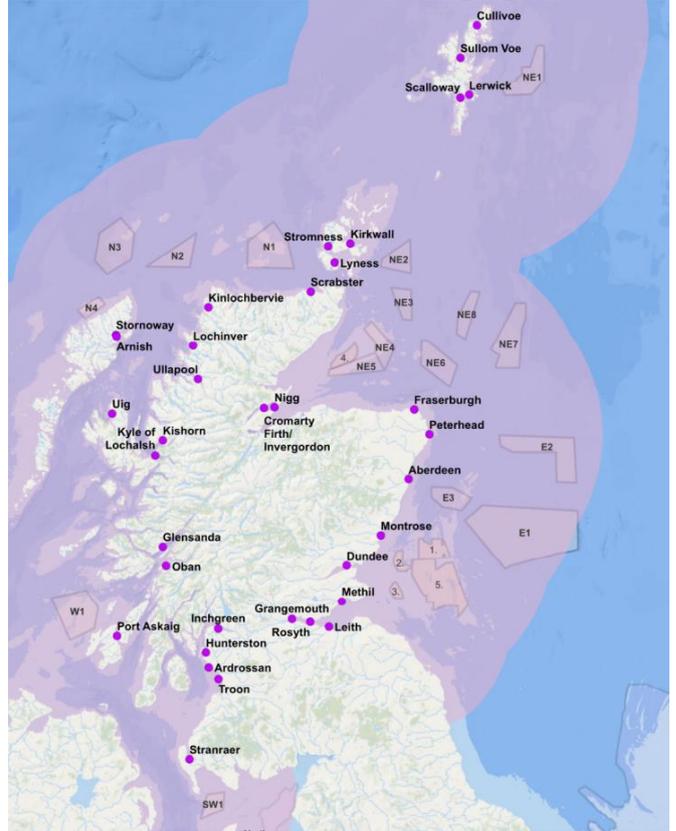
¹³ For context, the zones proposed for ScotWind Leasing have a theoretical maximum capacity of around 40-75GW if a development density of 3-5MW/km² is assumed. Irrespective of other factors, this is a high upper bound range that would be unlikely to be realised in practice as large areas will not be viable for development.

Figure 11: Ports meeting the assumed minimum hard criteria, with assumed ideal sailing distance from those ports highlighted as a combined catchment (see main text for further details). Main bathymetry shading indicates the 60m and 100m contours. Refer to Appendix C for full page versions.

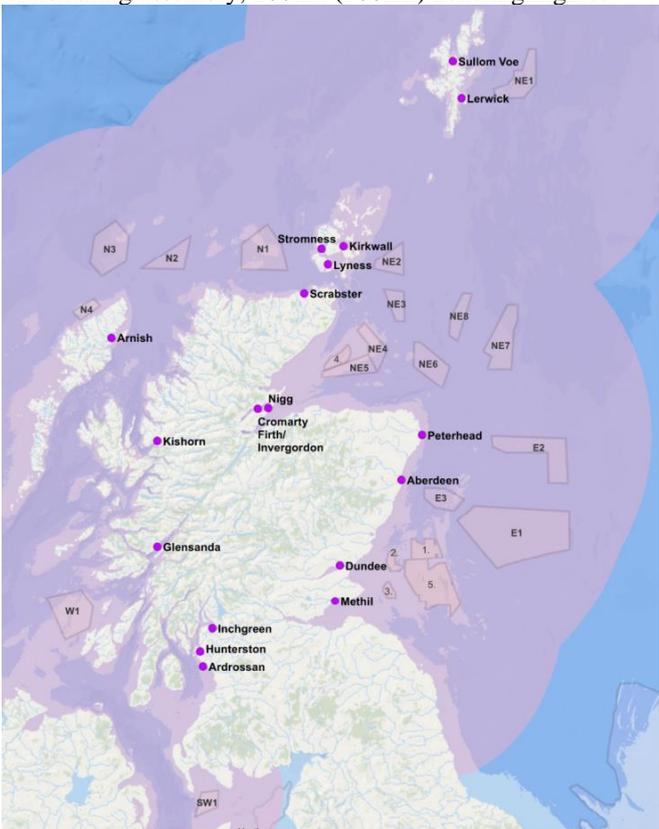
CTV based O&M, 75km (41nm) zone highlighted



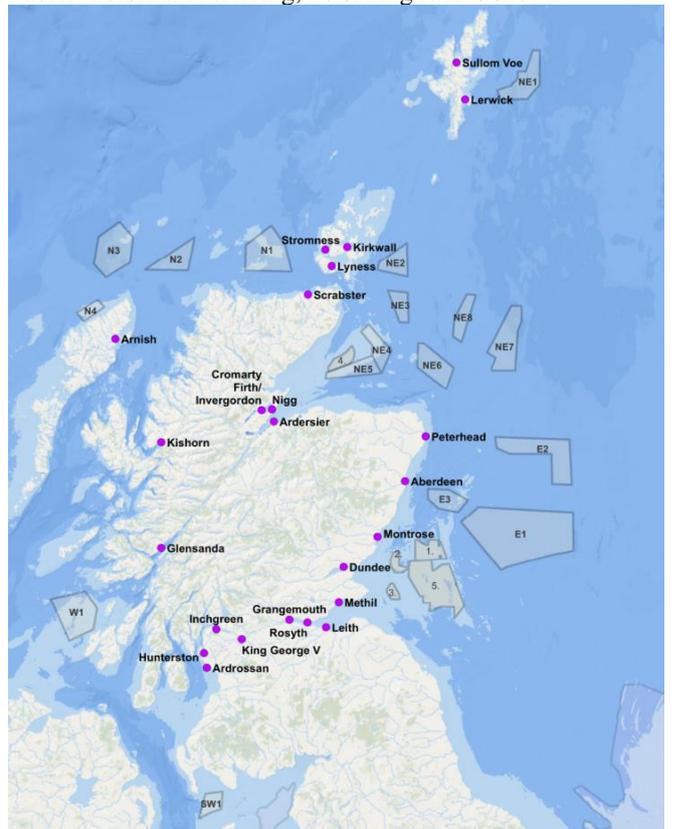
SOV based O&M, 150km (81nm) zone highlighted



Marshalling/assembly, 200km (108nm) zone highlighted



Fabrication/manufacturing, no sailing radius shown



4.3 Mini-clusters of ports with high suitability

The weighted multi-criteria assessment indicated geographic mini-clusters¹⁴ with high suitability across all or most of the four port functions. These mini-clusters include the following:

- Aberdeen, Peterhead and Fraserburgh – for SOV based O&M, marshalling/assembly and fabrication/manufacture these ports were consistently found to be well positioned relative to the development zones, where they pass the hard criteria. They also rate relatively highly in terms of port capability, and the Aberdeen South Harbour project is in progress, which will provide additional capacity.
- Orkney and Caithness ports – for all port uses they were consistently found to be well positioned relative to the development zones. Existing port capability for SOV based O&M is present. No ports in this cluster have existing capability for marshalling/assembly or fabrication/manufacture, although high-level assessment indicates there is good potential to develop capability, both in terms of laydown areas, and large naturally sheltered water areas for berths and moorings for floating storage.
- Cromarty Firth ports (Nigg and Invergordon) – for the large ports uses of marshalling/assembly and fabrication/manufacturing they are well positioned relative to zones in the Moray Firth, are reasonably well positioned relative to the rest of the development zones, and have very good existing capability for all port uses. High-level assessment indicates there is good potential to develop further capacity if required given large naturally sheltered water areas which may be suitable for reclamation for additional onshore areas, and for development of additional berths and moorings for floating storage.

For marshalling/assembly functions specifically, it is possible to refine the list of ports assessed to have high suitability to nine mini-clusters of ports and individual ports, and the development zones within the primary catchment of each (see Figure 12).

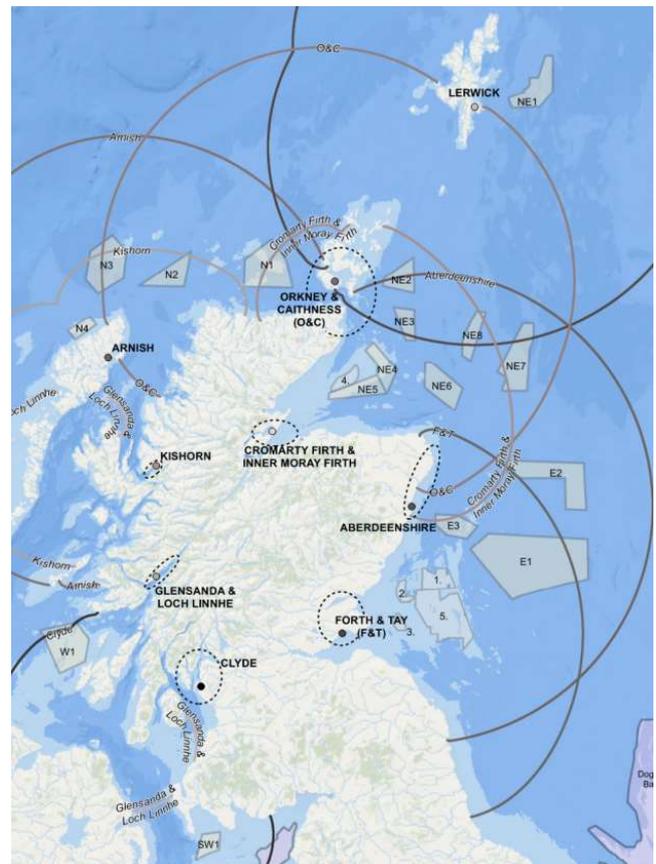
4.4 Sensitivity of proximity to fixed vs floating zones (60m contour)

The sensitivity of the distance-to-zone part of the assessment exercise was tested controlling for zone depth. Two additional runs of the distance analysis were undertaken: for likely fixed-bottom zones only, and for likely floating technology zones only.

It was assumed that zones with a mean water depth shallower than 60m would be developed with fixed foundation technology, and zones with a mean depth greater than 60m would be developed with floating foundation technology¹⁵. In reality there is likely to be no hard limit for either technology.

The assessment was found to be relatively insensitive to changing this variable. Therefore, broadly the same ports could be expected to support both types of zones, if they have the capability to do so. This should be considered in the design of future infrastructure upgrades.

Figure 12: 200km (108nm) sailing distance perimeters from nine groupings of ports with marshalling/assembly potential. Refer to Appendix C for full page version.



¹⁴ The term ‘mini-clusters’ is used here to differentiate the small geographic groupings of ports discussed in this study from the DeepWind Cluster and Forth & Tay Cluster, which are industry groupings encouraging offshore wind supply chain development coordinated by HIE and SE respectively [18][19].

¹⁵ Bathymetry data derived from reference [20].

4.5 Market concentration

Analysis of the distance relationships between ports meeting hard criteria for each use and the offshore development zones was carried out. The analysis identified how many ports are within the assumed ideal distance of each zone for the port uses deemed to be sensitive to distance. This showed that, due to the dispersed nature of Scotland's ports and future windfarm zones, there are cases where there are three ports or fewer within the assumed ideal sailing distance of a given development zone for a given port use.

Considering the ScotWind and pre ScotWind zones only, the scenarios include:

- CTV based O&M:
 - Six zones where no ports are within ideal sailing distance.
 - An additional seven offshore zones have only one or two ports within ideal sailing distance.
 - An additional twelve offshore zones have only three ports within ideal sailing distance.
- SOV based O&M:
 - Three zones have only three ports within ideal sailing distance.
- Marshalling/assembly:
 - Four zones have only three ports within ideal sailing distance.

These would be situations of reduced choice rather than 'no choice' in port-windfarm relationships and could also act to encourage the development of alternative methodologies less reliant on local ports. For example, for O&M the increased use of longer range SOVs, rather CTVs.

For marshalling/assembly, even where there are multiple ports within the ideal distance, situations of limited choice may arise due to projects requiring the use of two or three major facilities simultaneously, as has been seen in Scotland for two major recent projects (refer to section 3).

The assessment of distance-to-zone relationships in the multi-criteria assessment was partly based on the degree of port choice available, as discussed in this section. Inclusion of this feature was intended to help highlight those ports most likely to be used for multi-projects considering the expected large growth in the offshore wind industry over the next two decades.

4.6 Role of Scottish ports beyond Scotland, and vice-versa

4.6.1 Non-Scottish port support to development zones in Scottish waters

A non-comprehensive sample of eleven 'competitor ports' from the rest of the UK and continental Europe was included in the distance-to-zone analysis for comparative purposes. No other data was considered for these ports.

The results showed that none of these eleven ports are better geographically positioned for the Scottish development zones overall than the Scottish ports. However, there are individual ports within viable distance to provide distance-sensitive port functions for specific Scottish zones. The sampled ports in the North-East of England although not within the assumed ideal 200km (108nm) distance of the future Scottish zones were found to be within a broadly viable 400km (216nm).

4.6.2 Scottish port support to development zones beyond Scotland

Ports elsewhere in the UK are better geographically positioned than Scottish ports for supporting distance sensitive functions for The Crown Estate (TCE) Round 4 development zones. This is demonstrated by the data in Table 3, which compares proximity to the Dogger Bank Round 4 zone to a sample of key ports. Although Scottish ports are not within the assumed ideal 200km (108nm) distance, the distances remain viable under 400km (216nm), and in particular could support the business case of Scottish ports with manufacturing/fabrication functions.

Table 3: Distance of selected ports relative to the centre of the Round 4 Dogger Bank zone.

Port / mini-cluster of ports	Approximate sailing distance to centre of TCE Round 4 Dogger Bank zone
Forth & Tay	350km
Aberdeenshire	350km
Cromarty Firth	520km
Orkney	550km
Tees	203km
Humber	213km
Great Yarmouth	255km

4.7 Existing port development proposals review

4.7.1 Extent of review

A sample of port masterplans and development proposals for ten ports considered to have significant potential for offshore wind use was reviewed¹⁶. The purpose of this exercise was to provide comment on their strategic suitability considering Scotland as a whole, and not to provide detailed comment on individual schemes.

4.7.2 Common features

Recurring features were noted across several, but not all, of the proposed schemes including;

- flexible, multi-use facilities, targeted at offshore energy and project cargoes in general;
- new quays designed to accommodate one or two 100-200m long vessels, with dredged depths approximately -10 to -12mCD;
- new laydown yards or working areas of 4-8ha;
- statements of aspiration to accommodate offshore wind or general offshore renewables O&M and construction activities; and
- minimal explicit phasing or future proofing proposals for subsequent expansions (within the public domain versions of the plans at least).

4.7.3 Discussion

We consider that broadly, the schemes on their own would be well suited for SOV based O&M activities, or for small- to medium-scale marshalling/assembly or fabrication/manufacturing. However, a facility with the characteristics described above would not have enough capacity to act as a major facility for these later functions.

We believe that there could be an opportunity to achieve greater benefits for Scotland collectively if more ambitious facilities are developed, as facilities with greater capacity would help enable the maximisation of the offshore wind deployment rate as is needed to meet the net-zero targets and ensure wider economic-activity benefits are brought onshore in Scotland. This is linked to the potential demand for large port capacity discussed further in section 6. More ambitious facilities, for example in terms of quay depths may also be needed to maximise potential for development of floating technology in Scotland, discussed further in section 5.

Designing port expansions and upgrades with the next phase of expansion already planned in outline would help ensure the opportunities available from larger facilities remain possible to achieve. Safeguarding of prime sites for major uses should also be considered. From a Scotland-wide strategic perspective, development of O&M facilities or other port functions that could be located elsewhere should be prevented at sites with potential for additional deep-water quays, large open laydown areas and nearby floating storage. Under current market mechanisms such safeguarding may not be perceived to be in the best interests of port operators who must consider opportunities as they arise.

¹⁶ In so far as they were available in the public domain, references [21]-[26].

4.8 O&M suitability conclusions

The distribution of the ScotWind Leasing zones is such that a mix of CTV and SOV based O&M will likely be required, with significantly greater SOV use than in the offshore wind industry to date. Potential locations for long-term multi-project hubs should therefore have capability to support both models.

Ports well positioned relative to potential development zones, that have a minimum of adequate existing capability, and for which O&M would be an appropriate use (i.e. would not preclude other larger offshore wind uses), include; Montrose, Aberdeen, Peterhead, Scrabster, Kirkwall, Stromness and Lerwick. Fraserburgh, Wick and Stornoway are similarly well geographically placed; Fraserburgh and Wick already support CTV based O&M. However, they would likely require more significant upgrades to support multiple projects and SOV based O&M. Many smaller ports could likely support CTV based O&M only for one or two projects, such as Eyemouth which has been selected as the O&M port for an upcoming project.

Availability of port capacity was not considered in detail in this study. We expect it may be an issue for most of the above ports if they are to become hub facilities accommodating more than one or two typical 1GW projects. We expect there to be constraints both for berths and onshore yard and O&M building areas. The capacity of existing infrastructure and water and onshore space could likely be maximised by shared-use approaches. This could take the form of shared quays and immediately adjacent areas for marshalling small loads and craneage, larger shared warehousing rather than multiple small warehouses. This is different to the typical model in the industry to date of O&M facilities segregated by windfarm operator.

Without undertaking major harbour expansion works requiring breakwater extensions or similar, it is our view that minor capacity improvements (such as one or two additional SOV berths) could likely be achieved at Montrose, Peterhead and Scrabster. More significant capacity improvements (of the order of three or four additional SOV berths with direct connectivity to associated onshore facilities) could be readily achieved in Orkney, Shetland and at Stornoway. At other locations more substantial harbour expansions would be required.

Where existing development proposals were reviewed, we considered that they were generally appropriate for SOV based O&M use. Some proposals have over-specified characteristics for O&M use, but under-specified characteristics for large offshore wind uses. However, non-offshore wind uses and flexibility for unknowns are also targets for many of these development proposals.

4.9 Large port suitability conclusions

Additional port capacity that is suitable for marshalling/assembly and fabrication/manufacturing is likely to be required in Scotland (see section 6). Opportunities for providing this additional capacity could include the following ports (order does not indicate any ranking):

- Stornoway/Arnish and Orkney do not currently have the infrastructure suitable for providing the functions at a large scale, but are considered to present strong opportunities for new infrastructure. This is on the basis that they are well placed for the potential market and have large sheltered water areas, which indicates that new facilities could be developed without major breakwater works. Stornoway/Arnish is noted to have existing proposals in place that are appropriate in terms of technical characteristics.
- West coast locations such as Hunterston and Kishorn are likely to be more relevant to supporting floating deployment, discussed in more detail in the following section.
- Lerwick/Dales Voe has suitable existing capability and is well placed for serving offshore development local to Shetland but is not centrally located for the potential market as a whole.
- Nigg and Invergordon, have suitable existing capability, have been used for recent major projects, are relatively well positioned relative to the zones considered, and have development proposals in place or underway for further capacity which are appropriate in terms of technical characteristics.
- Ardersier is reasonably well located relative to the development zones considered but is currently unused and would require major quay and dredging works to be viable. It has significant potential in terms of onshore yard area due to its former industrial use.

- The Aberdeenshire coast (principally Peterhead) along with Caithness (Scrabster and Wick) are well located relative to the zones considered, but major capacity improvements could be expected to be relatively higher cost at these locations due to lack of natural sheltering available on the coastline.
- Aberdeen itself is well located and is already subject to a major expansion. The characteristics of the direct onshore laydown area at the under-construction Aberdeen South Harbour would suggest that it will be better suited to supporting fabrication/manufacturing located outside the immediate port boundaries in the local area, also capitalising on the size of the local population and skills base. To support typical marshalling/assembly functions for more than one 1GW nominal project would likely require additional onshore laydown area.
- Dundee, Methil and Rosyth have suitable existing capability and experience of offshore wind uses. Dundee is planned to be used for turbine assembly for a major project under development, Methil has a history of hosting fabrication activities, and Rosyth has been used for substation topsides fabrication and hosts fabrication for other sectors. They are well located relative to the more southerly Scottish zones considered and are the best located Scottish ports relative to the Dogger Bank zone, off the coast of North-East England.

5. Port capability for floating wind

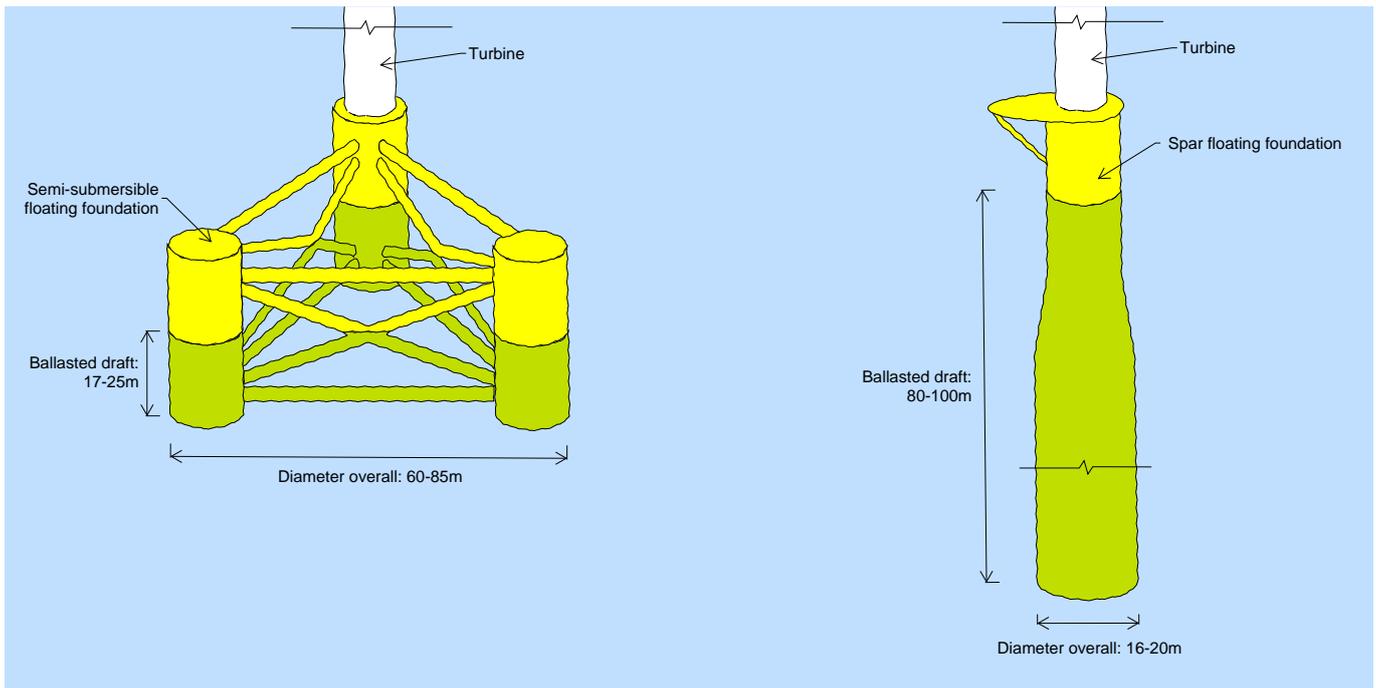
Key points:

- **Port requirements for floating are less certain** than for fixed-bottom offshore wind, particularly for the final assembly processes.
- **Distance sensitivity of ports to windfarms may be less for floating than for fixed-bottom**, influenced by possible factors such as lower cost installation vessels and the potential for use of intermediate floating storage locations remote from ports. However, we expect some degree of distance sensitivity to remain as port proximity to site will still be beneficial for reducing risks associated with the installation campaign, for example the risk of weather delays for component transport to site.
- **Additional specialist port facilities** for the final stages of the floating turbine assembly process may be required:
 - For **semi-submersible final assembly**, such facilities may require 20-25m water depth for foundation and turbine assembly alongside a quay. If distance relative to the deployment zones is considered the dominant variable, they would be best located on the Cromarty Firth and/or Scapa Flow. In both cases there are strong synergies with positioning for fixed-bottom deployment. Shetland and west coast locations are also capable of providing facilities but would be more remote from the expected offshore sites. The criticality of this will depend on the risk costs that come to be associated with distance to site for floating deployment, as noted above.
 - For **vertically-formed spar final assembly**, Loch Kishorn is the location of an existing facility and has the greatest water depth available to access open sea (80-90m). Hunterston and Clyde estuary, Glensanda and Loch Linnhe, and Shetland have intermediate water depths available (40-60m).
 - Alternatively, floating methodologies could be developed that rely only on conventional port facilities, such as **horizontal float out of spars and assembly at site** or at a sheltered location elsewhere on route. We expect that the direction of technology evolution will be partly dependent on the facilities that are available, both in Scotland and in other countries where floating technology is developed.
- **Conventional port facilities, as would be suitable for fixed-bottom deployment, are expected to be required as part of the floating supply chain in all scenarios.** This is because the quantum of floating components on a per turbine basis is expected to be broadly similar or greater than for fixed-bottom. As a consequence, similar transport vessels, yard areas and quay lengths will be required in the supply chain.

5.1 Introduction

The main assessment exercise (summarised in section 4) considered likely requirements for both fixed-bottom and floating technology. Requirements for fixed-bottom are more certain, therefore the main exercise risks being skewed towards those requirements. Additional conclusions regarding the suitability of ports in Scotland for floating are therefore provided in this section. These are focussed on spar and semi-submersible foundations, which were used as representative technologies for port assessment purposes.

Figure 13: Sketches of floating foundation types considered with assumed governing dimensions for 8-10MW units, refer to Appendix B for further details. Semi-submersibles (L); Spars (R).



5.2 Port requirements and provision

Ports requirements and logistics processes for floating wind were considered in the baseline review and have also been considered in other recent industry studies (including references [27]-[29]).

Uncertainty in port requirements will likely continue to persist for several years and therefore we recommend that the following principles are considered by all parties seeking to positively influence port provision;

- identify the better understood and more certain port requirements for floating, and seek to ensure that major port upgrade projects take them into account; and
- identify the less well-understood requirements and seek to ensure that the industry can test technologies at minimum commercial scale in Scotland, and in doing so identify the longer-term viable methodologies.

5.3 Port suitability

Port specific opportunities with respect to floating offshore wind are summarised in Figure D.1, Appendix D.

5.3.1 Port suitability for semi-submersibles – Scotland overview

Scottish ports were compared against key requirements for accommodating fabrication of semi-submersibles foundations and assembly with turbines, as summarised in Figure D.1, Appendix D. This analysis is based on our projections of the potential future sizes of semi-submersibles (see Appendix B), combined with our understanding of quayside construction techniques implemented or planned for demonstrator projects in the industry, the methodologies envisaged in industry reports and our views.

No ports in Scotland currently have a quay with adequate depth for quayside ballasting and assembly of a semi-submersible foundation for an 8MW turbine, if depths of 20-25m are assumed to be required (refer to technology projections in Appendix B). However, quays with adequate water depths of around 20-25m could feasibly be developed at a small number of Scottish ports.

Assembly methodologies away from quay may be feasible for ~8MW turbines using existing port infrastructure in Scotland. For example, several existing quays or dry docks with ~10-12m depths could be feasible for light (unballasted) float out of a foundation, followed by ballasting and assembly with the turbine away from the quay in deeper water alongside a jack-up vessel or similar.

We do not foresee it to be economically viable to develop fixed quays with depths of the magnitude the projections currently suggest could be required for foundations for turbines of 18MW or greater. We envisage that ports could therefore act as a limit on the technology and force it to evolve in a different way, or methodologies not wholly reliant on a fixed quay would need to be developed, for example assembly alongside ultra-heavy-duty pontoons on semi-permanent moorings.

5.3.2 Port suitability for semi-submersibles – specific opportunities

The review highlighted that, of the locations with characteristics that are likely to be adequate for the development of semi-submersible assembly capability, the Cromarty Firth and Scapa Flow would be best geographically positioned for development of such specialist facilities based on the assumed development zones. Shetland and west coast locations may also provide technically viable locations but are located further from zones. This observation is based on the area of zones with water depth greater than 60m within 200km, which is the assumed market available for the medium term. Therefore, this conclusion could change depending on the zones that are leased and developed.

We note that Lerwick (Dales Voe) is the proposed location for an “Ultra-deep-water Port” (UDWP) targeted at oil and gas decommissioning, as recommended in a 2018 study [30]. This facility would have similar and adequate quay capability for semi-submersible fabrication and assembly, and this could support the scheme’s business case. Nonetheless we would expect that additional Scottish facilities beyond the Dales Voe UDWP would be required should semi-submersibles become a dominant technology for wind deployment. Lerwick is not centrally located for the current ScotWind zones, and multiple facilities would likely be required to satisfy expected offshore wind build-out rates. An UDWP targeted at oil and gas decommissioning may also not have the availability and the scale of yard area required for mass fabrication, marshalling and assembly for the wind industry.

5.3.3 Port suitability for spars

We believe port requirements for fabrication and assembly of spar-based turbines in Scotland is less certain than for semi-submersibles.

Some methodologies used or considered in the industry, for example vertical slip forming and fully assembled vertical tow-out, have been designed around Norwegian bathymetry and infrastructure and would be transferrable to Scotland only in limited locations. This is principally due to the 90-120m envisaged ballasted draughts of foundations.

We envisage that development of spar-based windfarms in Scotland could entail one of the following broad methodologies:

- Construction of spars horizontally onshore, followed by largely separate foundation and turbine deployment in a similar manner to existing fixed-bottom windfarms. The spar foundation would be floated out horizontally from port or carried on a vessel to sufficiently deep water (either the final offshore site or a sea loch), before being up-righted, ballasted and the turbine attached. This would necessitate very similar port capability as for fixed-bottom windfarms.
- Development of a vertical construction methodology. This would entail linear piers in deep water and/or dry docks being used for an initial lift-out or fabrication stage, followed by subsequent joining of segments or slip-forming alongside a pontoon in 80-90m water depths. Of existing ports, Kishorn was the only location identified with ~80-90m water depth in its vicinity in a relatively sheltered area and with access of a similar depth to open sea. Hunterston and the wider Clyde estuary, and Glensanda and Loch Linnhe, may both be able to offer in excess of 90m depths in sheltered areas, but both are limited by ~40-60m depth access to open sea. Shetland also has water depths in this range. Assembly and installation methodologies would have to be designed around such constraints.

5.4 Role of dry docks

Dry dock capability in Scotland was captured as part of the data cataloguing exercise. The largest dry docks in plan area are located at Nigg, Kishorn and Hunterston. Each is large enough to accommodate simultaneous fabrication of one to four semi-submersible foundations of the assumed dimensions for existing generation, 8MW turbines (see Appendix B), but we expect that they may only be suitable for one or two future 15-18MW turbines. Their depth is only likely to be suitable for light float out of foundations, not ballasting and full assembly with turbines.

Similarly, dry-docks could be used in the early stages of spar construction. Therefore, we consider that the existing major dry docks may be of value to demonstrator, low volume early-commercial projects, and for some commercial projections for a stage in production, but that they are unlikely to be the sole means of production for commercial projects of the order of 1GW or more.

We would also note that dry docks are highly expensive infrastructure to develop compared to conventional quays and are more limited in flexibility of use. Development of additional major dry-dock capacity would be a greater risk than development of general quay and laydown capacity. Therefore, in the long-term we expect the industry would seek to limit their use unless a clear cost advantage can be identified sufficiently far in advance of commercial scale deployment.

5.5 Comparison with port requirements for fixed-bottom technology

5.5.1 Yard areas

Large open onshore storage areas in marshalling/assembly ports close to the offshore site has been identified as a requirement of current economic installation methodologies for fixed-bottom offshore wind.

Broadly, we expect floating wind foundations to require a similar or greater quantity of fabricated steel and/or concrete than their fixed-bottom equivalents on a per turbine basis. Foundations for each turbine are also likely to be broadly similar or larger in terms of plan area for a single turbine (e.g. spar compared to an XL monopile, semi-submersible compared to a jacket). We therefore expect the order of magnitude of storage area required within the floating wind supply chain to be the same as for an equivalent number of fixed-bottom turbines.

A floating-storage approach to marshalling large numbers of pre-assembled foundations with turbines relatively close to the offshore site may be viable for floating foundations. This is particularly likely for semi-submersibles, the expected drafts of which are within the depth range available in many Scottish sea lochs and estuaries. Floating storage feasibility for fully assembled spars with turbines is less certain due to the much greater depth requirements.

We therefore consider that it is likely that large onshore areas, of the scale required for fixed-bottom marshalling/assembly, will still be required for floating foundations. However, it may be feasible for these to be located at a greater distance from the offshore site if significant floating storage moorings close to offshore sites can be developed.

5.5.2 Quays

Transport vessel movements of a similar number and scale could be expected for floating as for fixed-bottom, given the above observations on quantities. This would logically be best accommodated at conventional deep-water quays of the type required for fixed-bottom deployment (around 10-12m depth), to minimise the extent to which specialist ultra-deep facilities have to be developed.

6. Demand

Key points:

- There is a significant risk that demand for port capacity in Scotland for large scale uses in the offshore wind construction phase may exceed current capacity within the 2020s or 2030s. This assumes a continuation of logistics and construction methodologies broadly like those used currently.
- There is a large range of uncertainty associated with these projections, primarily due to the continuing rapid evolution of offshore wind technology and methodologies. These uncertainties are such that we do not expect that more in-depth analysis in the short term would significantly reduce them.
- Port capacity that is less than demand could have the following implications;
 - slowed sector-wide build-out rate, with implications for the feasibility of achieving the net-zero target for Scotland, and particularly the UK-wide net-zero target;
 - adoption of less port-intensive construction methodologies, with implications for the level of activities associated with offshore wind occurring onshore in Scotland; and/or
 - inability to adopt the methodologies employed for the major recent Scottish, rest-of-UK and other northern European projects associated with current price expectations for offshore wind. The implications of this for the price of offshore wind in Scotland has not been assessed as part of this study.
- Major port infrastructure development timeframes are relatively long when compared to the programmes of individual offshore wind projects and the rapid evolution of the offshore wind industry.
- Public bodies, ports, offshore wind developers and the supply chain must weigh the risks of under-developing port capacity (including those noted above) against the risks of over-developing port capacity (including wasting natural and economic capital).

6.1 Introduction

A high-level assessment of the port capacity that will be required in Scotland to support future offshore wind construction has been carried out. There are significant uncertainties associated with future demand due to continuing technology and logistics methodology development and public policy. This assessment is therefore intended to demonstrate the issues involved and the expected order of magnitude of demand. As such, it should not be treated as a demand forecast.

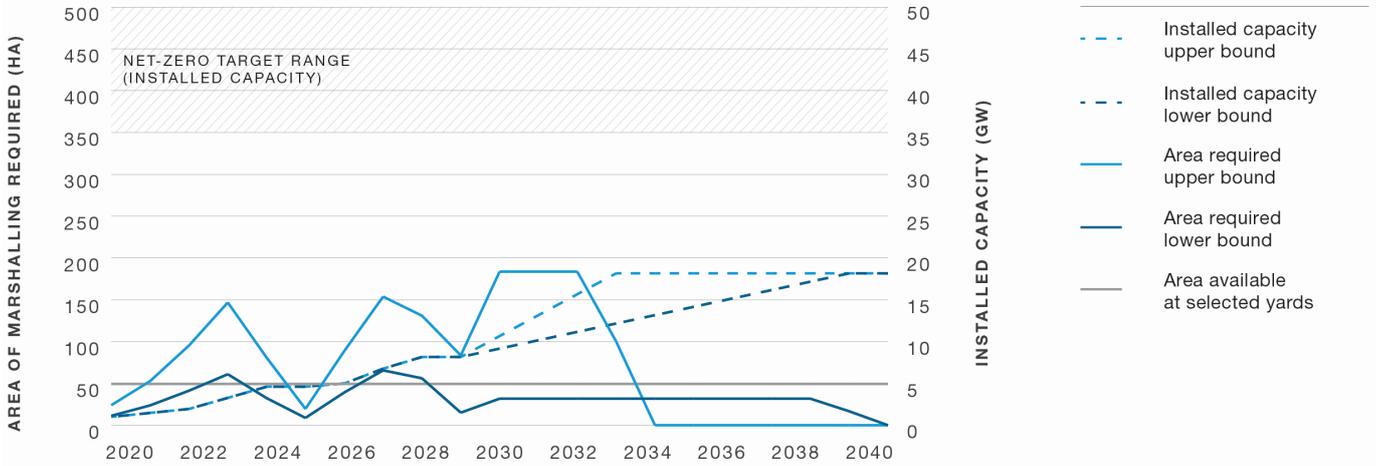
Laydown area, the open onshore storage area in a port, was used as the representative variable for port capacity in the assessment. It is typically one of the governing characteristics of ports that is considered in the design of offshore wind construction processes. It also provides a reasonably fair 'like-with-like' means of assessment when considering the whole ports sector. Large-scale fabrication, assembly and marshalling activities in open areas is one of the distinguishing features of port use for offshore wind.

6.2 Illustrative demand projections

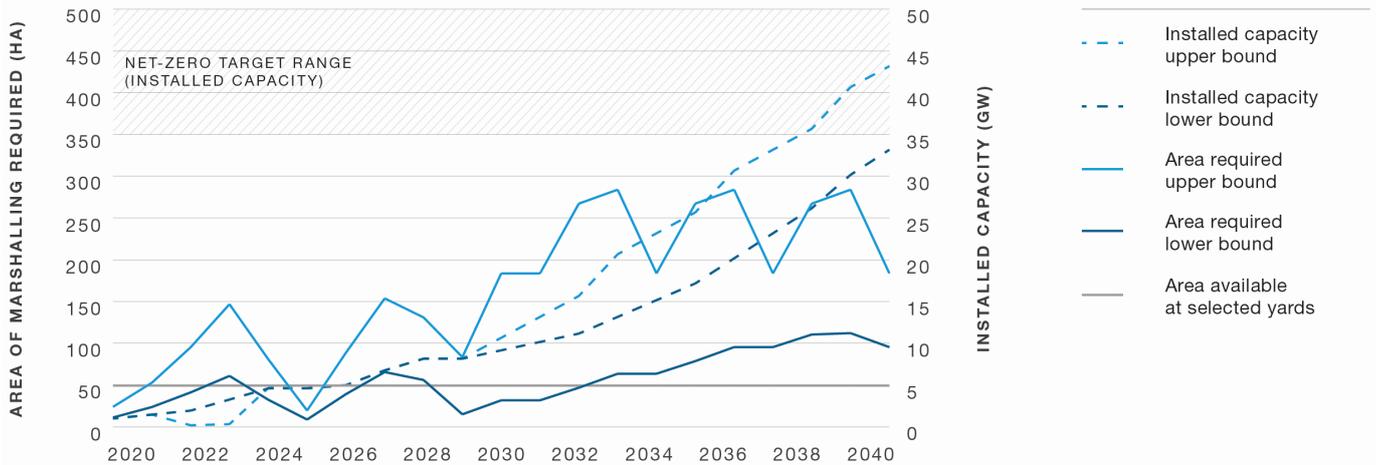
The illustrative demand projections are presented in Figure 14. Lower and upper bound scenarios are provided due to the range of variables involved, with multiple variable changes between the scenarios to characterise the sensitivity of the model used. These scenarios are intended to be reasonable estimates. More extreme scenarios could occur due to the uncertainties. Further background on the model used to derive the projections is provided later in this section.

Figure 14: Projected port onshore area demand for foundation and turbine component marshalling, and cumulative installed capacity of offshore wind in Scotland. Note that multiple variables are changed between upper and lower bound scenarios. For background on assumptions see discussion in main text. Top: pre-ScotWind and ScotWind 1 (10GW) deployment only. Bottom: pre-ScotWind and assumed successive ScotWind deployment rounds (10GW each).

Pre-ScotWind & ScotWind 1 only



Continuing deployment



6.3 Findings from illustrative demand projections

The projections highlight the sensitivity of port capacity requirements to the overall sector build-out rate and the offshore construction periods of single projects. There is significant potential for large peaks in demand due to projects coinciding with one another; this risk can be seen for build-out of already planned projects up to the mid-2020s.

The results indicate that foundation and turbine component storage alone may necessitate 100-200ha or more of dedicated marshalling/assembly areas in Scotland from the late 2020s. By way of comparison, half of the combined laydown area of six of the largest facilities would provide around 50ha¹⁷, assuming this proportion could be dedicated to offshore wind use. As shown by the distance analysis, the distribution of ScotWind Leasing zones is such that non-Scottish ports are expected to have limited opportunity to service them for distance sensitive functions. On this basis there is likely to be enough demand to justify major port capacity expansion for marshalling/assembly or fabrication/manufacture uses.

¹⁷ A nominal 50% of the capacity of the combined laydown area of Nigg, Invergordon, Dundee, Methil, Arnish and the under-construction Aberdeen South Harbour is estimated to be 50ha.

Consequences of lack of development of sufficient port capacity in Scotland could include slowing Scotland's offshore wind build-out rate, causing developers and contractors to seek out alternative methodologies making less use of Scottish ports and increasing project costs. Conversely, development of excess capacity that is later proven to not be required risks wasting the financial capital of investors (whether public or private), significant embodied materials and carbon, and having unnecessary negative local environmental and social impacts.

Adequacy of port capacity is a significant risk for the offshore wind supply chain. The likelihood of a port capacity 'bottle-neck' happening may be greater than for other supply chain elements due to the length of time required for development of major new port infrastructure. For example, 5-10 years for a major port development, versus 1-2 years for a new installation vessel. Unless significant development of new port capacity begins at risk prior to the expected increases in demand, then there is a risk of reactive responses being too late and a continual lag between supply and demand resulting.

6.4 The net-zero context

The projections are based on a reference target for installed capacity of offshore wind in Scotland of 35-50GW, compared to a 2019 level of around 1GW. This assumes that around half of the offshore wind capacity required to meet the UK-wide net-zero target is installed in Scottish waters. As such, Scotland would be a net-exporter of wind power derived energy to the rest of the UK. A 2025-2040 build-out rate of approximately 2-3GW/year in Scotland would be consistent with an ambition of reaching the target early in the 2040s, recognising the 2045 target for net-zero in Scotland and that offshore wind is more advanced than other technologies required for decarbonisation when considering the UK-wide 2050 target.

The above assumed target can be compared to the following offshore wind build-out scenarios and targets for the UK:

- The UK Government target of 40GW of installed capacity by 2030 [31][32].
- The Committee on Climate Change (CCC) 2019 Net-Zero Technical Report Further Ambition scenario, which includes 75GW of installed capacity by 2050 [3].
- National Grid's Future Energy Scenarios: envisaging 65-95GW by 2050 [33].
- Internal Arup analysis, which suggests that in excess of 100GW of offshore wind installed capacity, linked to forms of energy storage, could be required by 2050. This would be in scenarios where more pessimistic assumptions are made with respect to other less-advanced technologies such as bioenergy with Carbon Capture and Storage (CCS).

6.5 Model assumptions

6.5.1 Overview

The projections presented in Figure 14 were derived using a simple 'bottom-up' model based on assumed storage area required per component with reference to recent major projects in northern Europe and forward projections for component scaling. A reasonably rational port layout with access strips was assumed, for example for storage of jacket foundations a stacking layout was assumed such that any individual jacket can be withdrawn from the stack without moving more than one other.

6.5.2 Storage onshore in Scotland

The projections assume that storage of components for a minimum period onshore at a port in Scotland is required irrespective of original locations of manufacture (i.e. components will be stored for a time either in a domestic manufacturing facility, or in an intermediate marshalling or assembly port). This is based on the assumed distance sensitivity of projects to the final ports of departure for major components and the methodologies employed on recent major fixed-bottom projects, as discussed in section 3. The model assumes as a baseline that two months' worth of build-out is stored onshore at a port somewhere in Scotland, subject to additional factors to account for inefficiencies in yard use during and between projects.

6.5.3 Components considered

The model considers marshalling or assembly areas for foundation and turbine components only. Other components such as export cables, inter-array cables, offshore substation foundation and topsides, and scour protection materials are not considered. This approach was considered appropriate given the level of detail of the exercise, the uncertainties inherent in the projections, and the fact that foundation and turbine components are the largest by mass and plan footprint. Other port activities during the construction phase, such as facilities to support construction monitoring or surveys, are also not included.

Lower-bound port area requirements per turbine were determined by comparison to fixed-bottom north European projects developed in the past five years. Upper bound area requirements have been estimated based on Arup internal projections for scaling of fixed-bottom component sizes up to 20MW turbine rating and 60m water depth. Increasing turbine rating is expected to result in a net-reduction in storage requirements, with the reduced number of turbines outweighing the greater area requirement per turbine.

A large proportion of the installed capacity build-out in the projections can be expected to use floating rather than fixed-bottom technology. Requirements for floating wind remain less certain. However, we expect onshore area requirements for floating components to be broadly similar or greater than for fixed bottom. This is based on Arup internal analysis which suggests the quantum of major fabricated components per equivalent turbine is likely to be broadly similar or greater in terms of both mass and plan footprint area. The projections implicitly assume that distance sensitivity of ports to windfarms remains, irrespective of the technology type.

6.5.4 Comparison with other port variables

Although this assessment has focussed on laydown area requirements, it can be treated as proxy for other port characteristics. For example, in a typical marshalling/assembly port, based on projects to date, we would expect a minimum of one berth sufficient to accommodate one major component transport or installation vessel (i.e. 140-240m long, 10-12m depth), to be required per 10ha of yard approximately.

6.6 Model uncertainties

Significant sources of uncertainty associated with the assessment are highlighted in Table 4.

Table 4: Sources of potential uncertainty in laydown area demand projections.

Potential change in market	Expected impact on demand for onshore storage in ports in Scotland
Demand for faster decarbonisation, offshore wind build-out rate increases	↑
Significant floating storage anchorages are developed (either for self-floating components, or other components on barges)	↓
Growth in demand for similar facilities for other industries (e.g. marine renewables, oil and gas decommissioning)	↑
Accelerated development of larger turbines	↓
Earlier take-up of floating instead of fixed-bottom	←→
Lower-cost offshore installation methodologies and lower-cost vessels make risk of delay in supply chain more economically acceptable (e.g. in delays transport or production)	↓
Project viability without CfD or other public financial support makes meeting of programme milestone dates less critical	↓
Numerous smaller facilities and/or sub-optimum layout facilities developed and used (i.e. greater inefficiencies)	↑
Fewer, but larger and highly efficient layout facilities developed and used (i.e. greater efficiencies)	↓
Geographically concentrated offshore development, resulting in reliance on a smaller number of ports	↑

Legend:

↑ Increase, ↓ Decrease, ←→ No significant difference

7. Findings

This section summarises the main findings of the study, with interpretive recommendations for next steps provided in the following section.

Finding 1: Port capability and capacity for operations and maintenance (O&M)

The locations and distribution of the ScotWind Leasing zones are such that a mix of smaller, shorter-range, Crew Transfer Vessel (CTV) and larger, longer-range, Service Operation Vessel (SOV) based O&M strategies will likely be required. We expect there to be significantly greater SOV use than in the offshore wind industry to date, based on distance from port alone.

There is broadly adequate technical port capability to support both CTV and SOV based O&M strategies. Capability is well distributed, with appropriate ports available for all the offshore development zones considered. However, we expect capacity to be constrained due to existing port uses and the scale of future offshore wind development, and that infrastructure upgrades will be justified in multiple locations to facilitate expansion of both berthing/water space and areas for associated onshore facilities.

We would expect O&M hubs for multiple projects to emerge at ports that can accommodate a mix of both CTV and SOV vessel classes.

Finding 2: Port capability and capacity for large construction uses (marshalling/assembly and fabrication/manufacturing)

Marshalling/assembly ports have been used as local final staging points between globally distributed supply chains and offshore sites on recent major projects across the UK and continental Europe. They are a key feature of the logistical methodologies, approach to risk management, and contractual arrangements of these projects and as such their use can be inferred to have been a contributing factor to increasing project scale and lower project costs.

Scotland has ports with adequate technical capability to support marshalling/assembly. However, they are limited in number, capacity and geographic distribution when compared to the future ScotWind zones. Several existing ports, although meeting minimum hard criteria, do not currently provide the same standard of infrastructure as is typically desired by some offshore wind developers and contractors to limit constraints on a project: For example onshore storage area to accommodate a buffer stock of a reasonable percentage of components, or unrestricted water depth of 10-12m below Chart Datum that is sufficient to allow the majority of the North Sea installation and transport vessel fleet to tender for work on a project.

A small number of ports in Scotland host a single offshore wind manufacturing function. Port capability for a single manufacturing function is typically less critical than for marshalling/assembly. For example, 24-hour vessel access irrespective of tides may be less critical if components are being shipped to an intermediate location and not directly to the offshore site.

There are currently no major 'hub' ports in Scotland providing co-located marshalling/assembly and fabrication/manufacturing on a scale comparable to the facilities that have been developed in the past 10 years of the offshore wind industry at ports in other North Sea countries. Examples of these include Rotterdam and Vlissingen (both Netherlands), Cuxhaven (Germany) and Esbjerg (Denmark).

Significant additional marshalling/assembly port capacity in Scotland is likely to be required in the form of sites with adequate laydown areas, quays to simultaneously accommodate multiple large transport and installation vessels and component transfers, and opportunities for development of floating storage moorings. This conclusion is based on a high-level assessment of demand using onshore laydown area as a representative port characteristic. The capacity gap is predicted to occur irrespective of whether fabrication of components occurs in Scotland or elsewhere.

Four of the ScotWind zones have three ports or fewer within an assumed ideal sailing distance of 200km for marshalling/assembly, also considering other assumed hard criteria. Based on recent examples including the

largest projects in Scotland to date, a nominal 0.5-1GW offshore wind project requires two marshalling/assembly ports in parallel during construction – further emphasising that these ports have a high chance of use if the relevant zones are developed.

Finding 3: Suitability of current port development plans for offshore wind

Several ports in Scotland have existing development proposals that would provide additional technical capability and capacity, which would be of benefit to the offshore wind sector. The majority of development proposals are not solely targeted at the offshore wind sector.

Considering SOV based O&M use, individual proposals are broadly technically appropriate or in excess of what would be required for this use alone. The adequacy of development proposals to support fabrication/manufacturing and marshalling/assembly is mixed; some proposals contain quay lengths and laydown areas that risk restricting the methodologies available to offshore developers/contractors to a greater extent than is the case elsewhere in the UK and Europe. If facilities are developed along these lines offshore wind project costs could be higher and the portion of offshore wind activities undertaken in Scotland may be less than would otherwise be the case.

The high-level demand assessment indicates that there is likely to be demand for larger and/or more facilities than those currently contained in the sample set of development proposals we have had sight of. This suggests a need for port owners and investors to review development plans where the offshore wind industry is a target market to ensure that plans are appropriate and as a minimum future proofed to allow for later phases of upgrade and expansion. This conclusion could be further substantiated by a more extensive review of port development proposals in dialogue with Scotland's ports.

Finding 4: Floating offshore wind and compatibility of facilities

Specialised infrastructure is likely to be required to support floating deployment, but requirements are more uncertain than for fixed-bottom due to the stage of development of the various competing technologies.

For semi-submersibles, this could include deeper water (20-25m) quays for floating assembly and large scale sheltered floating storage areas of similar depth or greater. No quays of this depth currently exist in the UK. The Cromarty Firth and Orkney (Scapa Flow) stand out as having significant potential for semi-submersible assembly facilities, based on existing or potential technical capability and their central positions relative to the development zones.

For spars, methodology requirements for additional infrastructure appear more uncertain but could include ports with the same capability as for fixed-bottom technology, followed by use of sheltered water areas of 80-90m+ depth if vertical assembly processes are used. Alternatively, there may be a demand for quays or linear piers over 20-30m+ water for initial vertical formation of spar bases, followed by further vertical fabrication and ballasting alongside vessels or heavy-duty pontoons in 80-90m or greater water depths. Assuming these requirements, Loch Kishorn stands out as having the most significant potential.

Existing dry-docks would likely be useful for demonstrator projects or discrete parts of commercial scale production processes (e.g. initial semi-submersible or spar base fabrication), and as such investment in improvements to the existing major facilities may be justified. However, due to their relatively high capital cost and absence of a clear technical requirement we do not believe there is a current case for development of major new dry docks.

We expect that facilities developed for the large port uses for fixed-bottom technology would also have capability and be in demand as part of the supply chain for floating. This is because the quantum of floating components in terms of mass and size is expected to be broadly similar or greater than for fixed-bottom. Specialised port infrastructure will be higher cost, which should incentivise the use of conventional port facilities wherever possible at intermediate stages in the supply chain. In addition, distance sensitivity of ports to windfarms is expected to remain to some extent, due to the risk costs associated with greater distance from point of assembly to the offshore site.

Finding 5: The strategic decarbonisation case for port investment created by the net-zero targets

Scottish ports operate in a free market. As such, expansion/upgrade decisions are based on business confidence in future demand. The rapid rate of offshore wind market evolution, and hence emergence of certainty in demand, compared to the relatively long lead-time for port upgrades means that there is a risk of continual under-supply in suitable port capacity.

The rapid offshore wind build-out rate required to meet the net-zero target is such that there may be a strategic decarbonisation case for taking port investment decisions sooner and at greater risk than has historically been the norm. This is because there is a counter-risk of continual under-supply in suitable port capacity due to the long-lead time for port upgrades relative to the rate of offshore wind market evolution.

In addition, the long design-life of port infrastructure is such that any upgrades implemented now will last beyond Scotland's 2045 net-zero carbon target. Any upgrade proposals must be compatible with a future fully decarbonised lifecycle for offshore wind such that they can be net-zero in operation. Considerations should include provision of local renewable energy supply for a manufacturing facility, zero-carbon fuel provision to vessels and to port equipment for component handling and assembly.

Finding 6: Suitable locations for expanding capacity for operations and maintenance (O&M), and development of potential hubs

We expect O&M activities to be developed at a wide range of ports due to the geographic distribution of existing capability and the distributed nature of the future development zones.

We believe that ports with the greatest potential to serve as multi-project hubs include, but are not limited to; Montrose, Aberdeen, Peterhead, Scrabster, Kirkwall, Stromness and Lerwick. This assessment is based on position relative to the potential development zones, existing capability to support both SOV and CTV methodologies, potential for future development, and appropriateness of O&M use (i.e. it would not preclude larger offshore wind uses). Fraserburgh, Wick and Stornoway are similarly well geographically placed; Fraserburgh and Wick already support CTV based O&M. However, they would likely require more significant upgrades to support SOV based O&M. Other ports may be suitable for CTV or SOV use only, or for use on individual projects. We also note that all port use on actual projects is subject to the decision-making processes of the organisations involved.

From a strategic Scotland-wide perspective, we would recommend that O&M activities are not developed where 'large' offshore wind port functions could otherwise be supported. However, we recognise that this may not be compatible with the commercial decision making of ports.

Finding 7: Suitable locations for expanding capacity for large construction phase uses, and development of potential hubs

Of the locations reviewed in this study, the Cromarty Firth and Inner Moray Firth, and Orkney and Caithness areas were found to be centrally located relative to the development zones. As such, they were assessed as being technically suitable to support multiple fixed-bottom and floating projects (particularly semi-submersible technology), providing long-term potential.

Aberdeenshire is geographically well located relative to the development zones and Aberdeen Harbour is already undergoing major expansion. However, further expansion of the type and scale required for the offshore wind industry on the Aberdeenshire coast would be expected to be costly relative to the other options due to topography. In addition, the greater water depths that may be required for floating component assembly are not available.

Further infrastructure development may be justified elsewhere but we consider that their viability will be more dependent on which areas are leased in the forthcoming ScotWind Leasing round, these include Stornoway/Arnish, Lerwick, Hunterston, and the ports in the Forth and Tay area. The latter may also find their business case strengthened by development of TCE Round 4 Dogger Bank Zone, with the same also true for ports in the North-East of England with respect to future Scottish offshore development.

Fabrication/manufacturing use of ports is noted to be product and business-specific and significantly influenced by non-port factors.

8. Recommendations

The following recommendations are targeted at CES and the other public sector project partners in accordance with the scope of the study.

Recommendation 1: Scotland should collectively aim to increase large port capacity that is suitable for marshalling and assembly activities, acting as a key enabling action for growth of domestic manufacturing

Development of large port capacity in Scotland that is well suited to the needs of the modern offshore wind sector for marshalling/assembly and manufacture/fabrication activities has been limited, both in terms of scale and number of locations. This contrasts with other North Sea countries such as the Netherlands, Germany and Denmark. This study has not explored the drivers for development of these facilities in other countries. Contributing factors are understood to include historically different models for port ownership, investment and industrial strategy, and in some but not all cases, early development of the manufacturing facilities that have acted as ‘anchor tenants’.

Irrespective of the reasons for any historic differences with other countries, the context for considering port development in Scotland now is radically different compared to three years ago. In that time the significant cost reductions offshore wind has achieved in the UK has become apparent via the Contracts for Difference (CfD) process [34][35], the importance of achieving net-zero has become more widely recognised, and the magnitude of offshore wind development required to achieve net-zero has become apparent.

Given this context, we recommend that public and private sectors collectively recognise that marshalling/assembly capacity should be prioritised, based on the following key factors;

- the build-out rate of offshore wind required to meet net-zero targets may not be achievable without significant expansion of marshalling/assembly port capacity. This risk needs to be considered against the counter-risk of over-developing of additional port capacity;
- development of offshore wind in Scotland at a competitive cost may not be achievable unless further marshalling/assembly capacity is developed. Recently completed or under development 0.5-1.0GW+ projects in Scotland and the rest of northern Europe have made extensive use of marshalling/ assembly facilities;
- the expected continued build-out associated with offshore wind from the late-2020s onwards should provide a more consistent stream of work and employment than has been perceived in the past – this will enhance the overall value case; and
- marshalling/assembly should not be seen as a distinct opportunity to fabrication/manufacture. On recent projects we are aware that more on-site works than planned have typically taken place in marshalling/assembly ports indicating the potential for organic growth into more manufacturing functions. Prospective investors in fabrication/manufacturing facilities would logically be likely to favour locations with adequate port capability already available.

The UK ports sector, including Scotland, currently operates in a free market with a limited role for the state. In this context, we recommend that the following ideas could be explored further;

- mechanisms for ports to be provided with long-term market confidence in offshore wind, and earlier certainty in individual offshore wind projects;
- mechanisms that encourage pooling of funds from multiple projects to support port infrastructure enhancements. This could have synergies with the existing industry collaboration clusters (Forth and Tay, and DeepWind), and could lead to the formation of more geographically localised ‘sub-clusters’ for industry collaboration. The recent shift from ~0.5-1GW projects to 3-4GW ‘pipeline projects’ under single developers may also assist this; and

- whether substantially different models of public and private collaboration are required in the ports sector. A key issue in the offshore wind context is the utility-like nature of ports, arising because O&M and marshalling/assembly port use is sensitive to distance and location, arguably more so than many traditional port uses.

We also note that there is significant international interest in the offshore wind and ports sectors around the idea of major hub ports, where multiple manufacturing and marshalling functions are co-located. This study did not consider in detail the merits of such a facility compared to the alternative of a more distributed model across multiple ports. However, we do make the following observations;

- a major manufacturing hub would be most cost-effective if it had a large area of offshore wind development within its own marshalling/assembly catchment, everything else being equal. However, to achieve manufacturing economies of scale it would likely also need to ship components to marshalling/assembly ports elsewhere for non-local projects;
- a major manufacturing hub would be unlikely to produce all, or even the majority of components, required for an offshore windfarm due to the complexity and scale of projects. A modern nominal 1GW project may source foundation and turbine components alone from ten or more manufacturers;
- based on the ScotWind zones, future offshore wind development off the coast of Scotland is relatively well distributed. No single port in Scotland is within the assumed ideal 200km sailing distance for marshalling/assembly of all ScotWind zones (see Figure 3). However, there are ports with significant potential for establishment of a hub that are within 300-350km of 14 of the 16 ScotWind zones, ignoring the two more remote west coast zones; and
- even if significant domestic manufacturing facilities are established, there will be competition from international manufacturing facilities, whose products, developers and lead contractors may procure instead. A major hub facility would need to allow for multiple developers, manufacturers and contractors, who may be commercial rivals, to work in parallel on multiple manufacturing and marshalling/assembly functions.

Recommendation 2: Support strategic port planning for offshore wind

There may be inadequate time available for a ‘business-as-usual’ approach of allowing the market to iterate towards a system that provides appropriate additional capacity, given the net-zero targets. Conversely, there is also a risk for ports that they develop either excess or over-specified capacity compared to the industry’s needs.

This creates an argument for a more strategic approach to planning of port developments targeted at offshore wind. We recommend that any approach to strategic planning would require a partnership of public and private bodies from both the ports and offshore wind sectors.

We also believe there are smaller readily achievable discrete activities that could be of value, such as;

- encouraging a focus across industry on taking actions that enhance long-term supply chain confidence. We note that the ScotWind Leasing process already contains requirements targeted at this;
- further development and publication of demand projections, noting the high-level nature and uncertainties associated with those published in this study;
- cross-industry involvement in the generation of a standardised, concise set of guidance on infrastructure requirements for offshore wind for the ports industry. This would include more certain requirements versus unknowns in relation to floating wind. Various sets of port requirements already exist in industry reports in the public domain and port requirements are discussed in outline in this study. However, further clarity may be beneficial in the industry to ensure appropriate and efficient upgrade proposals are developed and to provide further market confidence; and
- greater standardisation of forms of contract and leases between port operators and their offshore wind customers (i.e. developers and contractors), to help reduce contract formation costs and maximise time available for infrastructure improvements.

Recommendation 3: Encourage development of optimal O&M facilities

The study has identified that there are existing facilities that are adequate for both CTV and SOV based O&M. However, these facilities are dispersed, and the optimum facilities are likely to require additional capacity. The industry collectively should consider;

- development of additional capacity at the likely hub locations where multiple projects could be based. Multi-project O&M hubs may be more beneficial in rapidly developing a skills base and lowering costs. There would be a role for both the public and private sectors in promotion of hub locations. O&M is an area of relative UK strength in offshore wind, and as the industry continues to develop in Scotland this can be further built-upon;
- development of shared O&M facilities and infrastructure. Ports and harbours suited to O&M are typically in historic town-based locations with relatively constrained expansion potential. Shared facilities, such as office buildings, warehousing and berthing, could maximise available land and water space, and reduce the risks associated with individual offshore wind projects developing bespoke facilities in time for project completion; and
- whether smaller, remote harbours including those on islands, that could be used as O&M bases for individual projects should be supported. These locations may require more proactive promotion from outside parties, whether public or private sector, if they are to be used. Remote harbours could offer different benefits to more established harbours and potential hub locations, such as enhanced local community support for offshore wind and achievement of different social and economic objectives.

Definitions

Term	Definition
<i>Port use</i>	A use, function, or type of port as part of the offshore wind industry.
<i>Port function</i>	For the purposes of this study four port uses for offshore wind were considered:
<i>Port type</i>	<ul style="list-style-type: none"> • Crew Transfer Vessel (CTV) based operations and maintenance (O&M) port • Service Operation Vessel (SOV) based O&M port • Marshalling and/or assembly port • Fabrication and/or manufacturing port <p>These four port uses are broad categories and are intended to capture the typical previous and reasonably foreseeable logistics approaches for offshore wind projects. The division of functions between ports and distinctions can vary between projects.</p>
<i>Operations and maintenance (O&M) port</i>	<p>A port which is used to host activities associated with the ongoing reasonably foreseeable operation and maintenance activities associated with an offshore windfarm during its design life.</p> <p>Refer to section 2 for further details.</p>
<i>Marshalling and assembly port</i>	<p>A port which is used as an intermediate facility during construction phase of a windfarm.</p> <p>Refer to section 2 for further details.</p>
<i>Fabrication and manufacturing port</i>	<p>A port which is the original location of fabrication or manufacture of the components used on an offshore windfarm project.</p> <p>Refer to section 2 for further details.</p>
<i>Large offshore wind port</i>	<i>Marshalling / assembly ports</i> and/or <i>Fabrication / manufacturing ports</i>
<i>Large port use</i>	
<i>Fixed-bottom wind</i>	<p>Offshore wind turbines supported by foundations that transfer the weight of the installation directly into the seabed. Fixed-bottom foundation examples include monopiles, piled jackets, suction bucket jackets, and gravity bases.</p> <p>For the purposes of this study, <i>zones</i> were assumed to likely be developed with fixed-bottom technology if they had a 60m mean water depth or shallower.</p>
<i>Floating wind</i>	Offshore wind turbines supported by the buoyancy of a floating platform. Floating foundation examples include spars, semi-submersibles, and tension leg platforms.

Term	Definition
<i>Floating wind [cont.]</i>	For the purposes of this study, <i>zones</i> were assumed to likely be developed with floating technology if they have a mean water depth greater than 60m.
<i>ScotWind</i>	The Crown Estate Scotland managed seabed leasing process for future offshore wind development in Scotland, pre-launched in 2019 and launched in 2020.
<i>Areas of Search</i>	See Draft Sectoral Marine Plan for Offshore Wind Energy
<i>Draft Plan Areas</i>	
<i>Draft Sectoral Marine Plan for Offshore Wind Energy</i>	<p>The Marine Scotland developed plan identifying the Draft Plan Areas that, once finalised, are expected to become available for bids for lease option agreements as part of the ScotWind process.</p> <p>This study considered the Areas of Search defined in the internal Scottish Government working version of the plan which was current as of September 2019 [2], and which was subsequently published for public consultation on 18th December 2019 [1].</p>
<i>Round 4</i>	The Crown Estate managed seabed leasing process for future offshore wind development England, Wales and Northern Ireland, launched in 2019 and ongoing in 2020.
<i>Seabed Bidding Areas</i>	The areas of seabed available for bids for leasing as part of The Crown Estate's Round 4 process.
<i>Hard criteria</i>	The assumed minimum criteria against which certain characteristics of ports were checked as part of the analysis for this study. If all hard criteria for a given port use were satisfied, the port was considered in more detail for that <i>port use</i> .
<i>Realistic criteria and ideal criteria</i>	Additional criteria relating to port characteristics which were used for the derivation for the boundaries for the multi-criteria assessment undertaken for this study. Unlike <i>hard criteria</i> , realistic criteria did not need to be satisfied for a port to be considered for a given <i>port use</i> .
<i>Zone / offshore zone</i>	<p>An offshore area in which offshore wind development may be considered or pursued.</p> <p>Refer to section 4.1 for the details of the zones considered.</p>

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Appendix A: Hard criteria used in port assessment

Background

Hard criteria were applied for the four port uses in the assessment exercise. Hard criteria are conservative upper or lower bounds for key variables, which if not satisfied resulted in a port being ruled out.

The hard criteria were set with an optimistic margin compared to what we consider to be the realistic criteria for the given variables. Inclusion of this margin ensures that no viable ports that are narrowly outside of the realistic criteria and may in fact be viable due to port or windfarm specific circumstances, were prematurely excluded from the analysis. The magnitude of the margin applied in each case is based on judgement of the sensitivity of the analysis to that variable.

Hard criteria were applied to variables that are fixed (such as port location) or were deemed to have limited potential for change without major harbour redevelopment. For example, widening of existing harbour entrances, berth deepening.

No hard criteria have been applied to existing quay length and existing storage area. It is recognised that most candidate sites would otherwise be excluded as the industry requirements are not currently available at a large proportion of ports in Scotland.

Hard criteria for CTV based O&M

Table 5: Hard criteria assumed for CTV based O&M.

Variable	Hard criteria	Realistic criteria (for reference)	Key assumptions for hard criteria
Water Depth at Entrance	3m below Chart Datum (minimum)	3-4m	O&M ports must be accessible at all states of the tide. Depth allows for most of CTV market (e.g. 1.5-2.5m draught CTVs, plus under keel clearance and siltation allowance). The realistic criterion is already readily achieved by many ports well distributed around the coast, so the additional margin included when setting the hard criteria is minimal in this case.
Distance to closest offshore zone centroid	100km (54nm) (maximum)	50-75km (27-41nm)	2.0-2.5hours transit each way is the upper bound acceptable sailing time likely to be acceptable to provide 5-6hours at site for technicians during a typical 10-hour shift. 100km equivalent to 3hrs sailing at 18 knots, or 2.5hrs at 22knots.
Harbour Entrance Width	12m (minimum)	15-20m	Allows for some of the CTV vessels market (e.g. 9-10m beam).
Lock or gate restriction to port	Not acceptable	-	CTV based O&M strategies are time critical and the risk of even relatively short delays (e.g. 30mins) are unlikely to be accepted during port selection.
Air draught	No hard criteria applied	Unrestricted	Not applied - no ports included subject to the use-specific screening have a known air draught constraint that would be of significance for CTVs.
Onshore area suitability	0.75ha port land (minimum)	1.5-3ha	Subject to more detailed criteria for high-level judgement of onshore area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.
Water space suitability	40m turning area 1ha sheltered area (minimums)	2ha sheltered area	Subject to more detailed criteria for high-level assessment of sheltered water area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.

Hard criteria for SOV based O&M

Table 6: Hard criteria assumed for SOV based O&M.

Variable	Hard criteria	Realistic / ideal criteria	Key assumptions for hard criteria
Water Depth at Entrance	5m below Chart Datum (minimum)	7-8m	O&M ports must be accessible at all states of the tide. Allows some of the vessel market with recognition that a limited amount of further deepening may be possible which would allow a greater portion of the market.
Distance to closest offshore zone centroid	200km (108nm) (maximum)	100-150km (54-81nm)	200km equivalent to 6hrs sailing at average 18knots. Assumed that even in an SOV based strategy the O&M port must be in feasible sailing distance of the SOV on a regular basis (for example on a 2-weekly cycle) or of CTV shuttles. However, it is feasible for SOVs to operate significantly further than this from their home port. Port distribution around the coastline is such that a project would be unlikely to select a facility more than 200km from the windfarm, as there are likely to be adequate facilities within this range.
Harbour Entrance Width	18m (minimum)	20-25m	Allows for some of the SOV vessels market (e.g. c14m beam), note many of the emerging vessels are in the range 17-20m beam.
Lock or gate restriction to port	No hard criteria applied	Unrestricted	SOV based O&M strategies may tolerate the risk of delayed entry/departure from harbour if it met other criteria.
Air draught	No hard criteria applied	Unrestricted	Not applied as no ports included to the intermediate round of analysis have a constraint that would rule out most SOVs.
Onshore area suitability	0.75ha port land (minimum)	1.5-3.0ha	Subject to more detailed criteria for high-level judgement of onshore area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.
Water space suitability	120m turning area 1ha sheltered area (minimums)	2ha sheltered area	Subject to more detailed criteria for high-level assessment of sheltered water area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.

Hard criteria for marshalling / assembly

Table 7: Hard criteria assumed for marshalling/ assembly.

Variable	Hard criteria	Realistic / ideal criteria	Key assumptions for hard criteria
Water Depth at Entrance	6m below Chart Datum (minimum)	10-12m below chart datum	Must be accessible at all states of the tide to ensure cost efficient installation programme. 6m only allows for some of the vessel market but recognises that a limited amount of further deepening may be possible which would allow a greater portion of the market.
Distance to closest offshore zone centroid	400km (216nm) (maximum)	200km (108nm)	400km equivalent to 18 hours at 12knots or 27hours at 8 knots. Marshalling port proximity to sites noted to be highly cost sensitive due to high daily rates for installation vessels.
Harbour Entrance Width	25m	50-60m (fixed bottom technology)	Typical jack-up and heavy-lift installation vessels available in the market for fixed bottom installation are 40-50m beam. Any marshalling port used for multiple projects would need to be able to accommodate such vessels. Components such as blades can also overhang the beam of the vessel in some arrangements. Logistics processes and installation vessels for commercial-scale floating wind less certain, but as a minimum likely to require access for 20-30m beam general cargo vessels and 300ft class barges for import of large components.
Lock or gate restrictions	Not acceptable	-	For marshalling ports 24/7 access with minimal risk of delays is required due to the high cost of installation vessels
Air draught	80m	Unrestricted	Assumed that marshalling/assembly ports must be flexible enough to accommodate a range of offshore wind technologies. 80m would allow passage of some smaller jackets loaded vertically on transport vessels and some turbine installation vessels but would still act as a constraint on many.
Onshore area suitability	4ha port land (minimum)	6-12ha	Subject to more detailed criteria for high-level judgement of onshore area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.
Water space suitability	180m turning area 4ha sheltered area for floating storage (minimums)	180-280m turning area 4-12ha sheltered area	Subject to more detailed criteria for high-level assessment of sheltered water area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.

Hard criteria for fabrication / manufacturing

Table 8: Hard criteria assumed for fabrication/manufacturing.

Variable	Hard criteria	Realistic / ideal criteria	Key assumptions for hard criteria
Water Depth at Entrance	3m below Chart Datum (minimum)	10-12m	If used in combination with a marshalling port, a fabrication port may tolerate more limited vessel access (e.g. logistics processes designed around specific vessels or barges) and tidal access only may be acceptable.
Distance to closest offshore zone centroid	No hard criteria applied	N/A	Fabrication port location is not sensitive to offshore site location if marshalling port used.
Harbour Entrance Width	20m (minimum)	50-60m	Nominal minimum value based on inland waterways in continental Europe. For ocean going access and option of direct delivery to site, requirements would be the same as for marshalling ports.
Lock or gate restriction to port	No hard criteria applied	N/A	Delays may be tolerable.
Air draught	No hard criteria applied	N/A	Not applied as no ports included in the port-use specific screening have a constraint that would completely rule out use for fabrication/manufacture.
Onshore area suitability	4ha port land (minimum)	6-12ha	Subject to more detailed criteria for high-level judgement of onshore area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.
Water space suitability	180m turning area 4ha sheltered area for floating storage (minimums)	180-280m turning area 4-12ha sheltered area	Subject to more detailed criteria for high-level assessment of sheltered water area suitability. No realistic prospect of being developed into port type without excessive cost unless hard criteria met.

Appendix B: Reference vessel and component characteristics

Reference vessel characteristics

Table B.1: Assumed reference vessels used for definition of port capability requirements.

	Bound	Indicative reference vessel	Length Overall (m)	Berth length requirement assumed (m)	Turning circle req. (LOA x2)	Beam (m)	Entrance width requirement assumed (m)	Draught (m)	Depth requirement assumed (m)	Air draught (m)
CTV	Minimum viable	Current small CTV	18-20	20	40	8-10	12	2.0	3	12
CTV	Ideal	Current large CTVs	30-35	30	65	12-13	15	2-2.5	3	20
SOV	Minimum viable	Current small SOVs	50-60	60	120	14-16	18	4	5	30
SOV	Ideal	Current large SOVs	80-95	90	190	18-19	20	5.5-6.5	7	50
Manufacturing/fabrication	Minimum viable – inland waterway	Rhine barges	90	90	Not used	18	20	2.5	3	Not used
Marshalling/assembly and manufacturing/fabrication	Minimum viable	300' North Sea barge, General cargo vessel	90	90	180	27 20-30	25	3-5	6	40
Marshalling/assembly and manufacturing/fabrication	Ideal (lower)	Jack-up	140	140	280	40	45	6-7	8	100
Marshalling/assembly and manufacturing/fabrication	Ideal (upper)	Heavy lift or semi-sub	220-240	220	440	65	72	10	11	100

Notes

- Sources: Arup in-house databases, vessel builder and owner websites.
- The above reference characteristics were used for considering port requirements for the purposes of this study. They are intended for this purpose only.
- Reference vessels were selected based on a review of the current vessel market and consideration of likely future vessel requirements to 2040:
- O&M
 - Minimum viable – allows access for the minimum vessels required for the port to realistically function for that use.
 - Ideal – judged to likely allow majority of the vessel market in that class, excluding outliers
- Vessel needs relatively well understood as less dependency on turbine components
- Marshalling/assembly and manufacturing/fabrication:
 - Min. viable – as for O&M
 - Ideal upper/lower bound – bounds used to due to variability in current techniques and vessels, and uncertainty in future of installation methodologies and components
- Vessel characteristics rounded considering other typical vessels in the class.
- Does not include potential large future floating components, e.g. spars, semi-sub.

Reference component characteristics

Table B.2 Assumed turbine characteristics.

	15MW	20MW
Blade length	100-120m	120-150m
Rotor diameter	210-250m	250-310m
Nacelle mass	600-700te	800-1000te

Table B.3 Assumed monopile characteristics (40m water depth).

	15MW	20MW
Monopile diameter	10.0m	12.0m
Monopile length	85m	95m
Monopile mass	1350-1850te	2100-2900te

Table B.5 Assumed spar characteristics.

	10MW	15MW	20MW
Spar diameter	16-20m	20-26m	22-28m
Spar length	90-110m	100-135m	110-150m
Draft	80-100m	90-125m	100-140m

Notes

- Sources: future technology projections estimated using Arup in-house databases and concept sizing tools © Arup 2019.
- All values are noted to have uncertainties associated with them.
- The above reference characteristics were used for considering the port requirements in this study. They are intended for this purpose only.

Table B.4 Assumed jacket characteristics.

Water depth	Characteristics	15MW	20MW
60m	Jacket mass	1,250-1700te	1650-2300te
	Jacket footprint	34m x 34m	36m x 36m
80m	Jacket mass	1450-2000te	1950-2700te
	Jacket footprint	38m x 38m	40m x 40m

Table B.6 Assumed semi-submersible characteristics.

	8MW	18MW
Draft (ballasted)	17-25m	27-36m
Overall diameter	60-85m	120-160m

Appendix C: Ports assessed to meet hard criteria and sailing distance analysis summary

Figure C.1 – CTV based O&M, all ports meeting hard criteria

Figure C.2 – SOV based O&M, all ports meeting hard criteria

Figure C.3 – Marshalling and assembly, all ports meeting hard criteria

Figure C.4 – Marshalling and assembly, 200km (108nm) primary catchments from key port mini-clusters

Figure C.5 – Fabrication and manufacturing, all ports meeting hard criteria

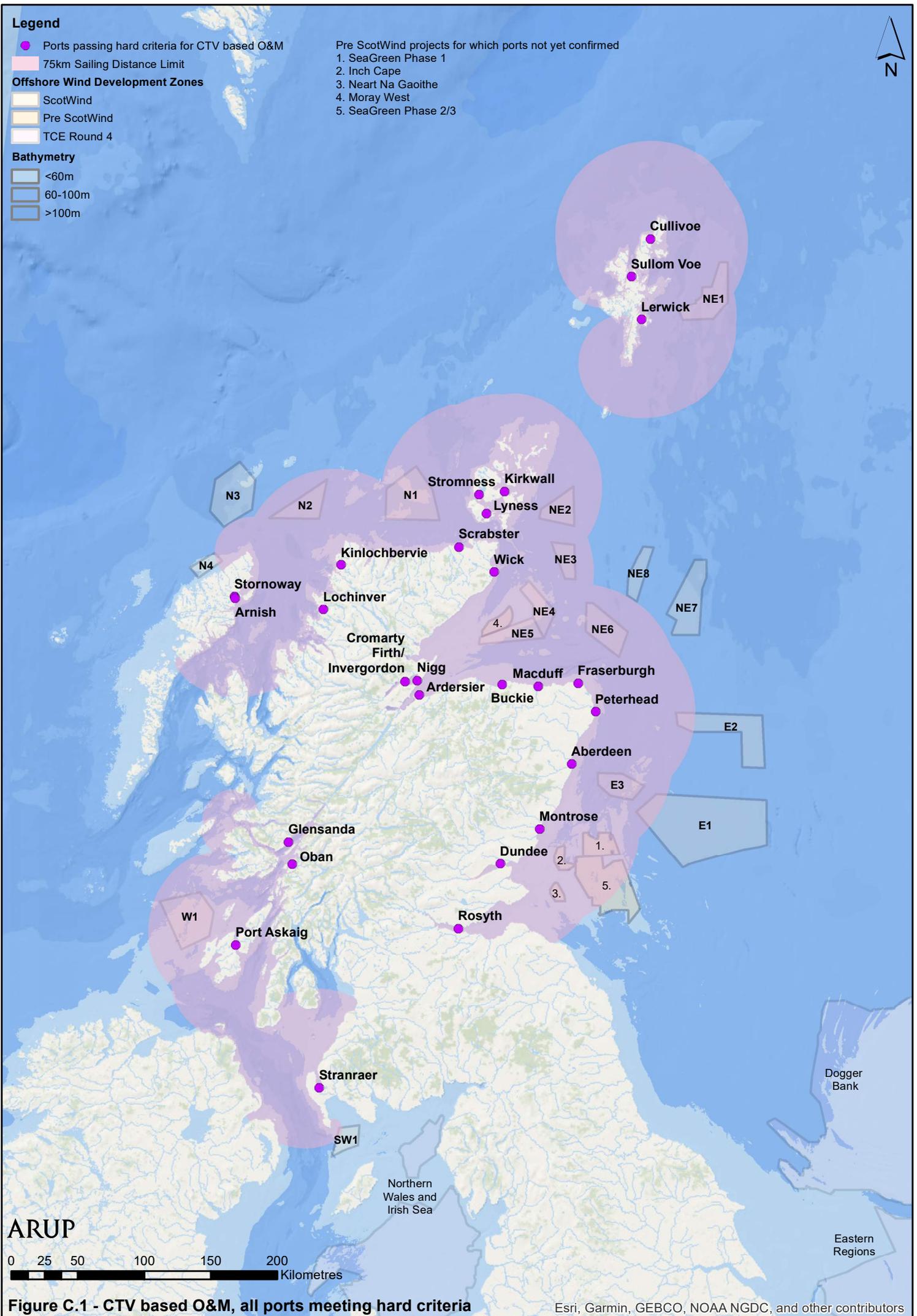


Figure C.1 - CTV based O&M, all ports meeting hard criteria

Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

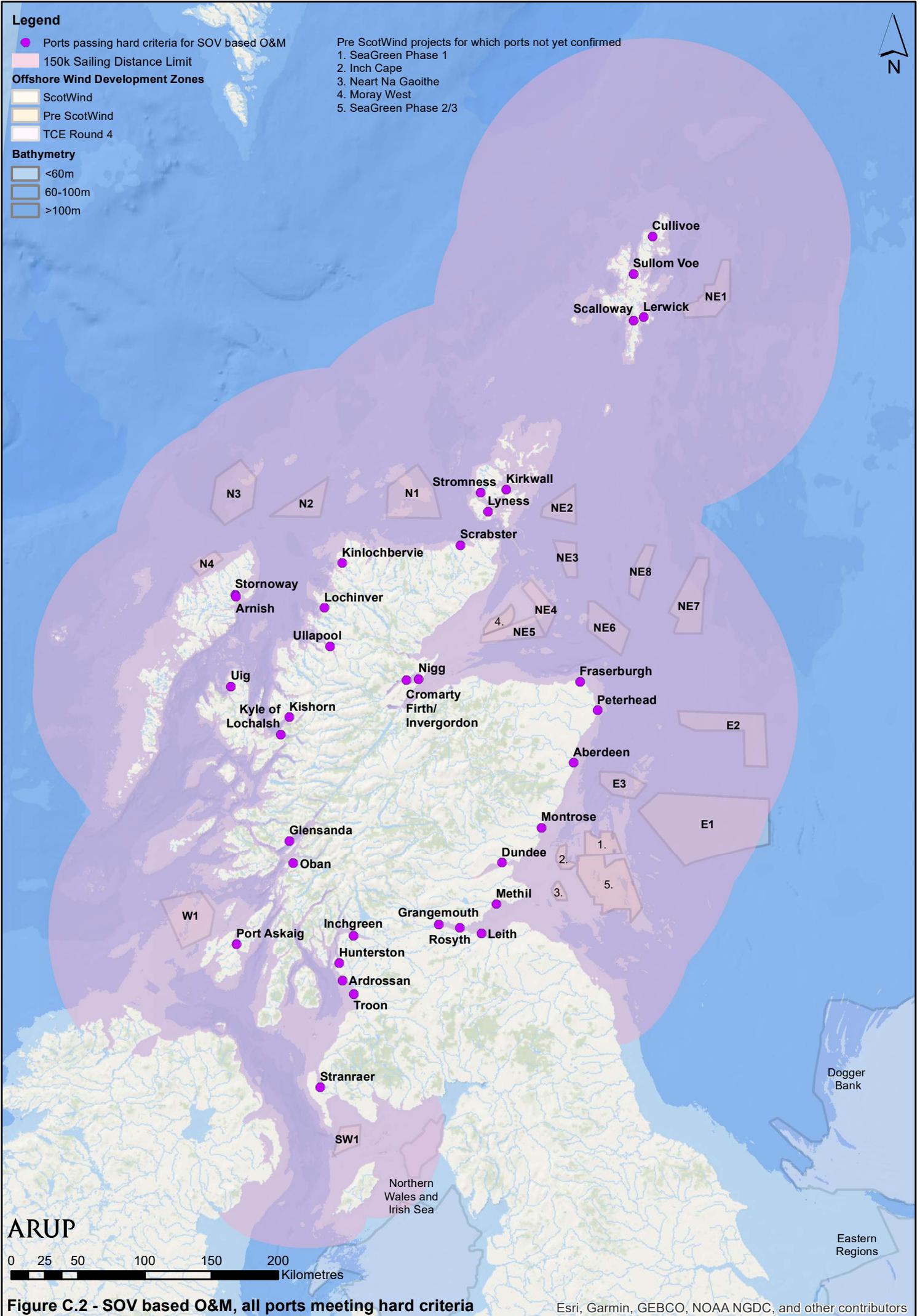


Figure C.2 - SOV based O&M, all ports meeting hard criteria

Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

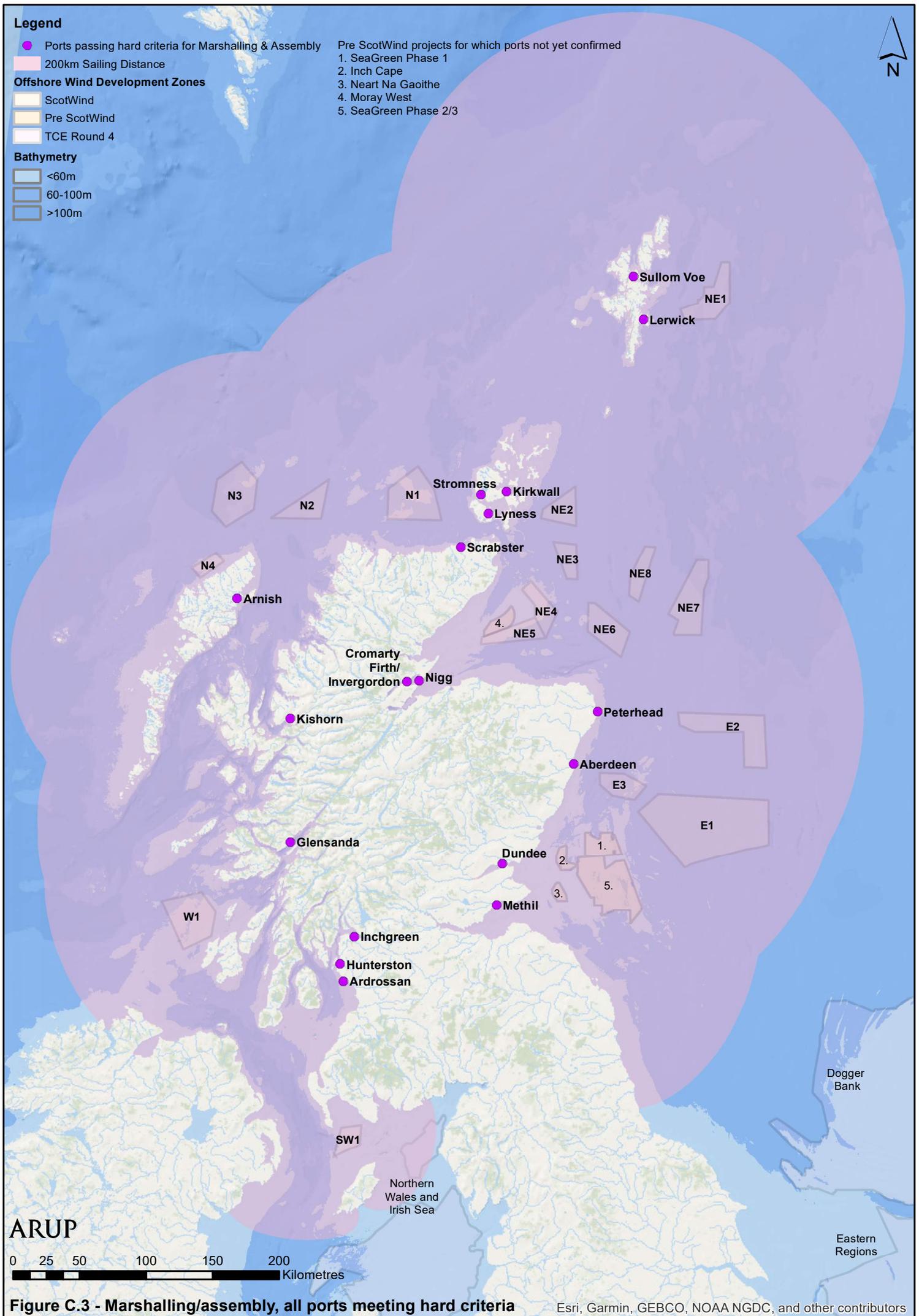
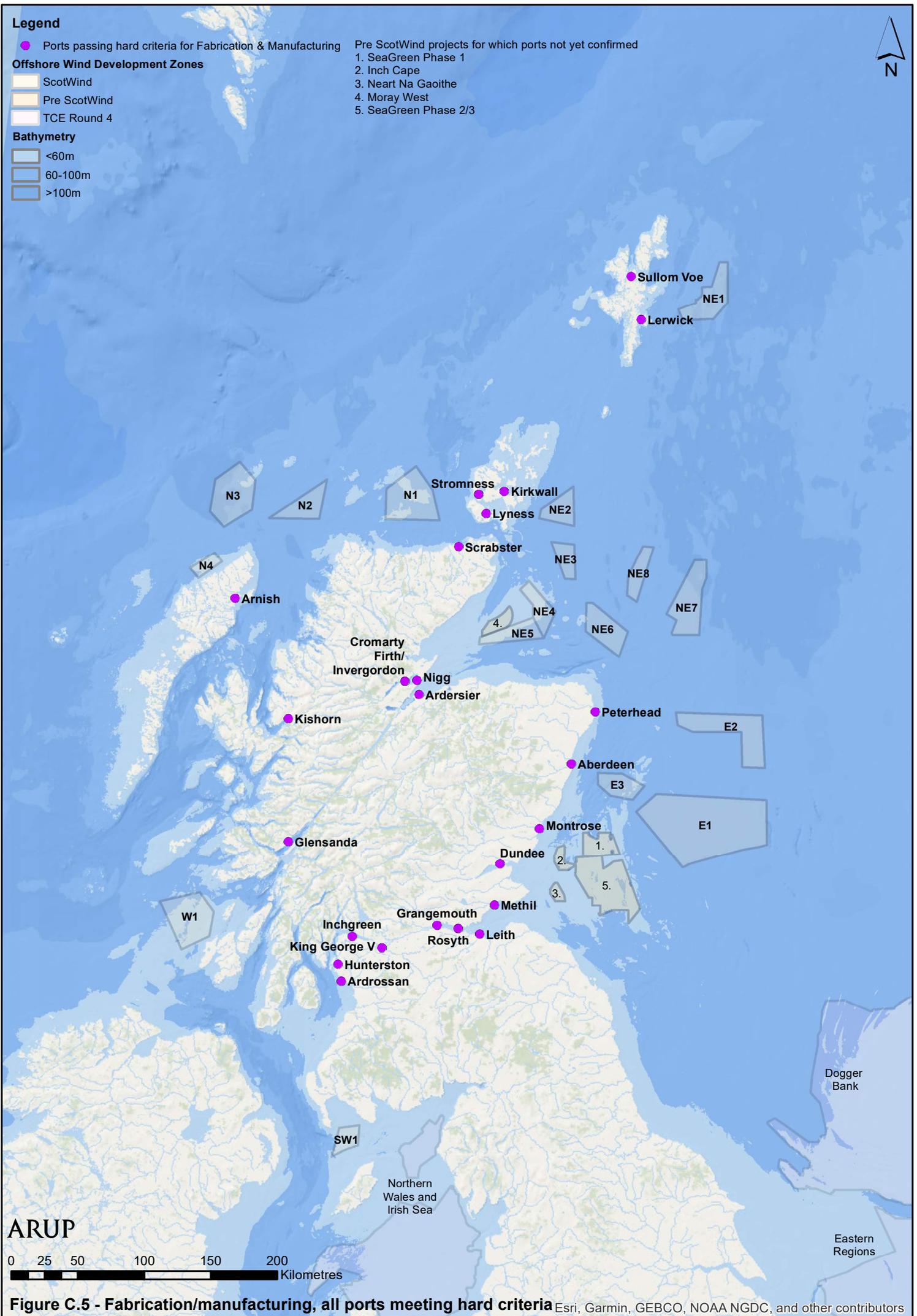




Figure C.4 - Marshalling and assembly, 200km (108nm) primary catchments from key port mini-clusters

Esri, Garmin, GEBCO, NOAA NGDC, and other contributors



Appendix D: Floating assembly – locations with high potential

Figure D.1: Floating offshore wind assembly – locations with high potential

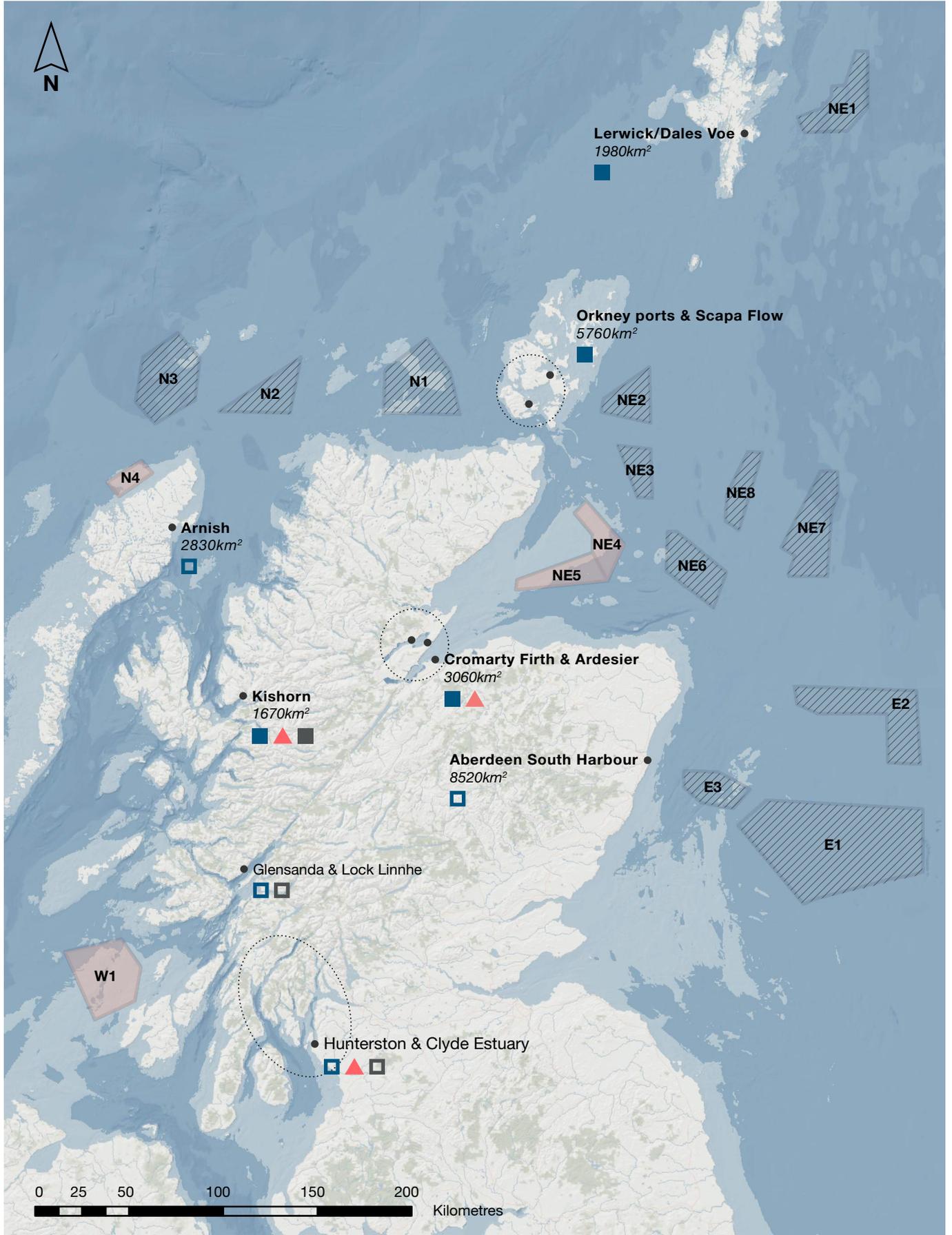


Figure D.1: Floating offshore wind assembly - locations with high potential

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Key



Semi-submersibles: floating assembly, fabrication and marshalling high-potential

Realistic potential* to achieve the following attributes:

- 20-25m+ water depth for floating assembly of deep draught semi-subs
- 90m min. access width
- 12ha (min.) onshore area for marshalling or fabrication
- 24ha (min.) sheltered floating storage
- Within 200km of ScotWind zones with mean depth >60m



Spars: floating vertical assembly high-potential

Realistic potential to achieve the following attributes:

- 80m+ depth sheltered water areas & route to sea
- 12ha (min.) onshore area for marshalling or fabrication
- 24ha (min.) sheltered floating storage
- Within 200km of ScotWind zones with mean depth >60m



Semi-submersibles: floating assembly, fabrication and marshalling potential

Realistic potential to achieve the following attributes:

- 9m+ water depth for conventional vessel load-out or light float out
- 90m min. access width
- 12ha+ min. onshore area for marshalling or fabrication



Spars: floating vertical assembly/staging potential

Realistic potential to achieve the following attributes:

- 50m+ depth sheltered water areas & route to sea
- Historic or current port use or other coastal industrial use



ScotWind leasing zone (draft)

Indicative floating technology zone (mean water depth >60m)



ScotWind leasing zone (draft)

Indicative fixed-bottom technology zone (mean water depth <60m)



Major dry docks

Realistic potential to achieve the following attributes:

- 60m+ clear entrance width
- 9m+ entrance depth



Port or group of ports



Geographic cluster of highlighted ports

5960km²

Area of ScotWind zones

Area of ScotWind zones with mean water depth >60m within 200km sailing distance.

Notes

- 'Realistic potential' taken to mean within confines of an established harbour without major breakwater or dredging works.
- A wider list of sites would be viable for fabrication or marshalling of individual components as part of multi-stage processes.

