The Workboat Association

CATAPULT Offshore Renewable Energy

DECARBONISING MARITIME OPERATIONS IN NORTH SEA OFFSHORE WIND O&M

Innovation Roadmap produced for the UK Government DfT and FCDO

CONTENTS

1 EXECUTIVE SUMMARY

The UK's offshore wind industry has seen rapid growth in the past ten years with more than 10.4GW of installed capacity now in UK waters and a target of 40GW by 2030. Meanwhile the European Union has set a 300GW target for 2050.

Currently, 79% of all European offshore wind (EU27 plus UK) is located in the North Sea and the region will remain one of the world's largest economic geographies for the foreseeable future.

During the Operations and Maintenance (O&M) phase of an offshore wind farm's lifecycle (typically estimated at 25-30 years), wind farm operators rely on extensive marine logistics between shore and the wind farm. The majority of vessels using Marine Gas Oil (MGO) and currently responsible for an estimated 284 kt CO_2e/ year. Engagement with wind farm owner operators suggests that there is a desire to reduce emissions associated with the Operations and Maintenance (O&M) of offshore wind through the adoption of clean maritime innovations.

The offshore wind industry has the potential to act as a 'springboard' industry, providing early adoption of technologies and market models that can assist a broader maritime decarbonisation. Recognising this potential the Department for Transport (DfT) and the Foreign, Commonwealth & Development Office (FCDO) commissioned ORE Catapult in partnership with the Workboat Association to develop a comprehensive Innovation Roadmap detailing how to decarbonise offshore wind vessels, with a particular focus on the North Sea.

The findings of the Roadmap are evidence-based and have been arrived at following desk based research, market scenario modelling and extensive industry engagement. The Roadmap, has been iteratively developed, drawing on insight gained from more than 25 in depth industry interviews and broader engagement and events involving more than 80 stakeholders from across the economic geography of the North Sea. A broad range of stakeholders were interviewed, both in terms of geography and function. Those interviewed included representatives from: Wind farm operators, turbine OEMs, vessel designers, shipyards and operators, class societies, port operators and alternative fuel and electrical charging infrastructure system designers, developers and operators

This breadth of engagement has helped to ensure that the findings reflect challenges and opportunities commonly recognised throughout the industry rather than focussing on issues that affect only a smaller sub-section of offshore wind stakeholders.

The Roadmap produced by ORE Catapult and the Workboat Association on behalf of the Department for Transport and the Foreign, Commonwealth & Development Office, provides:A

- An overview of market growth scenarios, that outline the known and anticipated growth profiles for offshore wind, the associated maritime logistics and the number of O&M vessels. The model includes three potential decarbonisation scenarios, the status quo, moderate adoption and accelerated adoption. The 'status quo' scenario considers low levels of clean maritime adoption with 95% of vessels continuing to use conventional fuel by 2025. The "accelerated" scenario considers the other end of the spectrum and is based on one third of North Sea O&M vessels in offshore wind adopting greener technologies by 2025 rising to 90% by 2030 in order to deliver near to full decarbonisation.
- A review of current and emergent technologies relevant to clean maritime operations in offshore wind O&M, including:
    - Propulsion types
    - Hull types
    - Alternative fuel production
    - Distribution and storage
    - Electrification
    - Charging systems and batteries, offshore logistics, operational performance and enabling infrastructure, and port logistics and enabling infrastructure.
- Identification of the key barriers to adoption of clean maritime technology in offshore wind, including: Economic, policy/regulatory, structural, organisational and behavioural barriers, including:
    - The cost differential between conventional marine fuels and alternative electrical or clean maritime fuels.
    - The high capital cost of emerging clean maritime technologies and the need for demonstration support to break the 'chicken and egg' challenge. This describes the current situation wherein it is difficult for operators to invest in clean maritime vessels in the absence of clean maritime infrastructure and vice versa .
    - A lack of clarity over future fuel pathways and the resulting lack of infrastructure and investment security.
    - The incentive support structures for offshore wind in many North Sea nations and the downward cost pressures this places on the supply chain.
    - Imperfect data concerning current emissions baselines and the performance of clean maritime alternatives.
    - Challenges concerning spatial and grid constraints in ports and the high capital costs of infrastructure upgrades.
    - The large numbers of existing vessels and the need to consider the challenge of retrofitting vessels.
    - The lack of any clear direction in terms of targets or deadlines for transition to clean maritime in the industry.

- Identification of a combination of measures designed to provide a roadmap to clean maritime operations. The roadmap includes proposals for four main areas of activity ranging from focused R&D, enhanced demonstration and the delivery of a number of potential enabling actions. By adopting the suggested enabling actions governments, industry and other stakeholders can address the key market, policy and regulatory barriers to transition. This would in turn enable the 'accelerated' maritime decarbonisation scenario for offshore wind in the North Sea. These enabling actions include:
    - Greater support for clean maritime demonstration at scale, in order to help address the chicken and egg challenge and build confidence in emerging clean maritime systems.
    - A need for clarity as to the transition timeline and deadlines for decarbonising North Sea OSW O&M in order to provide clarity to operators and investors and establish a 'level playing field' where first movers will not be 'undercut' by competitors.
    - Support for port operators to deliver the infrastructure required to ensure ports are equipped to support clean maritime operations.
    - Approaches to address carbon pricing and the cost differential between high carbon conventional fuels and low/zero carbon alternatives.
    - Incentives to address the challenge of retrofitting existing vessel fleets.
    - A need for greater collaborative innovation, both horizontally between wind farm operators, and vertically through the offshore wind and maritime supply chains.

There is broad support for an accelerated transition to clean maritime operations in North Sea OSW O&M and much of the technology exists to deliver this vision. Nevertheless, many non-technical barriers remain and will need to be addressed in order to deliver the vision and unlock the social benefits and economic opportunity presented by the accelerated transition.

There is common acceptance of the importance and need for targets in order to set clear expectations and establish a 'level playing field' among competitors. Though any drive toward targets and deadlines will require complementary financial support and incentives to enable the supply chain to rise to the challenge and make the necessary adjustments to transition.

This will require concerted and strategic action from North Sea Governments and industry, and greater collaboration between offshore wind developers and the maritime supply chain.

Table 1-1 summarises the barriers to decarbonising maritime operations in North Sea offshore wind O&M found in this report. For each barrier an enabling action is suggested with an identified actor(s) who is best placed to carry them out.

Table 1-1: Barriers to clean maritime adoption and associated Enabling Action.

Barrier	Enabling action	Actor (who can enable this?)
Cost differential between conventional and alternative fuels **Capital cost of clean maritime technologies** **Cost of capital (Finance)** **Lack of knowledge of future fuel cost** **Limited profit margins available**	**1.** More flexible, larger funding sources are essential for demonstrations of clean maritime technologies due to their complexity. This will be essential to bring cost parity of alternative and conventional fuels until they achieve economies of scale and encourage competitors to collaborate. **2.** Encourage O&M fleet decarbonisation through public policy exemptions to balance operating cost increases (including retrofitting incentives). For instance, innovative decarbonisation measures could be supported through The Crown Estate's Leasing Rounds by offering rental discounts or CfD auction mechanisms that encourage/mandate dedicated funding for maritime decarbonisation. **3.** Development of a Cost Reduction Monitoring Framework (CRMF) similar to that developed in offshore wind to set trajectories for cost reduction of offshore wind and conduct ongoing annual monitoring against plans.	Governments Grant awarding bodies Agencies/Organisations awarding Seabed Leasing/ CfD or other incentive mechanisms Government, Industry, Research Community, Research Technology Organisations (RTOs)
Lack of clarity over fuel pathways	**4.** Ensure that North Sea maritime decarbonisation is included in the cross-departmental Hydrogen Strategy within the UK Government. A clarity over fuel pathways is crucial for ports and vessel operators to secure investments in alternative fuel infrastructure see case study: Germany's National Hydrogen Strategy.	Government
Disproportionate carbon pricing	**5.** Consider pricing of fossil fuels used in maritime sector. Fiscal measures aimed at impacting the price of conventional fuels would improve the business case for clean maritime technologies.	Governments
Safety codes for new fuels and electrical marine charging systems	**6.** Establish a programme of work that will progress and develop safety codes and standards for lower emission fuels and electrical charging systems in tandem with the R&D/ Demonstration of technologies.	Governments, Regulators, Industry, Class Societies
Lack of standards	**7.** Engage with and help shape European initiatives to develop North Sea hydrogen infrastructure for OSW farms. **8.** Guarantee a collaboration mechanism to build on existing links between UK researchers, companies and European counterparts. **9.** To accelerate complex demonstration projects, make regulatory sandpits easy to access and multiagency; lessons should be learned from the integrated approach to innovation of the Oil and Gas Authority (OGA), the O&G regulator.	Governments, Industry, Regulators, Research Community, RTOs, Class Societies Governments, Research community, RTOs Governments, Regulators
Lack of targets and deadlines	**10.** Establish a 'level playing field' and provide investor confidence by establishing short, medium and long-term maritime decarbonisation targets to demonstrate ambition and encourage organisations to make plans and investments. **11.** Ensure that the national infrastructure commission supports the hydrogen infrastructure needs around ports.	Governments and/or Industry Government
Imperfect information about emissions	**12.** Develop standardised emissions data collection for O&M vessels and identify emissions baseline.	Governments, Industry, Research Community, RTOs, Class Societies
Existing port infrastructure **Portside electrical power constraints**	**13.** The £70m offshore wind manufacturing investment support scheme for major portside hubs is an important step in developing an infrastructure fit for purpose. Further funding to tackle infrastructure within ports will be necessary.	Governments (National and Regional)

Barrier	Enabling action	Actor (who can enable this?)
Split incentives	**14.** Development of an OPEX incentive for investing in clean maritime technologies.	Governments
Contract lengths	**15.** A common industry approach to longer charter durations for clean maritime vessels would provide greater investor confidence and support a move to investment in OSW clean maritime.	Industry
Lack of in field performance data	**16.** Development of common data benchmarking system similar to SPARTA in offshore wind. Using anonymised and aggregated data and providing industry benchmarking for clean maritime performance (including vessel, ports, alternative fuel and electrical charging infrastructure).	Governments, Industry, Research Community, RTOs
Lack of horizontal collaboration between competitors	**17.** Greater support and encouragement for Joint Industry Programmes (including aspects of R&D/Demonstration) including collaboration between government(s), regulators, class societies, industry and the supply chain on technical and non-technical work.	Governments, Industry, Regulators, Research Community, RTOs, Class Societies.
Lack of vertical collaboration along the supply chain		

2 INTRODUCTION

The UK's offshore wind industry has seen rapid growth in the past ten years with more than 10.4 GW of installed capacity now in UK waters totalling to 2,300 turbines. Meanwhile there is more than 25 GW of installed capacity in European waters (including the UK fleet) of which 80% is located in the North Sea. [1].

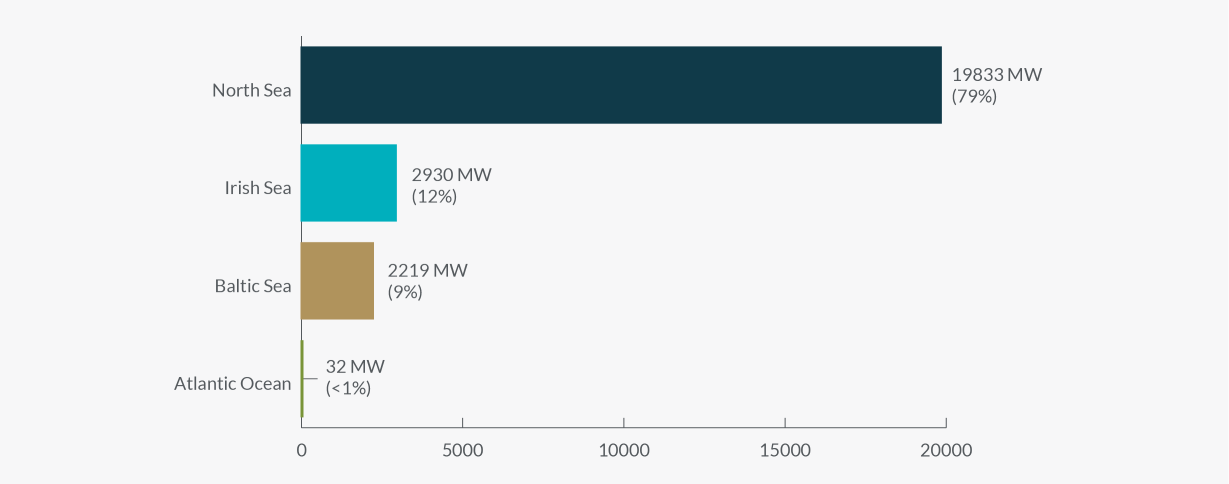


Figure 2.1: Cumulative installed capacity by sea basin (MW) [1].

The development of offshore renewables at scale is a key ambition for both the UK and the European Union, with the UK's Climate Change Committee highlighting the need for at least 100 GW of offshore wind to meet UK's net zero ambitions and the European Union having set a 300 GW target for 2050. The development of offshore wind at scale is a major success story for the UK and the EU as governments seek to deliver on net zero ambitions. Offshore wind farms require extensive marine operations throughout all stages of their lifecycle, including Development, Installation, Commissioning, Operations, Maintenance (O&M) and Decommissioning.

During the O&M phase of an offshore wind farm's lifecycle (typically estimated at 25-30 years), wind farm operators rely on extensive marine logistics between shore and the wind farm including the transportation and accommodation of technicians and the movement and storage of parts and tools. These are essential marine operations required to deliver a combination of planned and unplanned inspection, maintenance and repair works necessary to ensure the continued operational performance of turbines and other associated offshore infrastructure.

Of the maritime logistics deployed to support offshore wind farms, the vast majority of vessels are conventionally fuelled using Marine Gas Oil (MGO). This results in maritime emissions that many of the leading offshore wind industry partners are keen to reduce.

In its annual 'Sustainability Report' 2019, one of the major wind farm owner operators, Ørsted, reported emissions of 42 kt CO_2e from the Crew Transfer and Service Operations Vessels (CTVs and SOVs) that it charters to undertake the O&M of its offshore wind farms. These wind farms account for 12,000 GWh of electricity production and a 17% share of total installed European capacity. Extrapolating Orsted's figures suggests that maritime logistics in European offshore wind O&M could account for approximately 250 kt CO_2e per year with a carbon intensity of 3.5 t CO_2e per GWh.

It should be noted that emission data is taken from a 2019 data source as O&M emission data for 2020 was not considered to be representative due to the operational impact of Covid. 2019 figures are therefore taken as more representative of current emissions levels and applied to 2020 installed capacity and electricity generation.

The UK government is committed to net zero targets by 2050 with a recent commitment to achieving a 68% reduction in GHG emissions by the end of the decade [2]. This will include a decarbonisation of power production in which the offshore wind industry is already a major contributor providing ~10% of the UK's electricity in 2020 [3].

In support of these net zero targets, the UK Clean Maritime Plan (CMP) sets out Government's intention to support a high level of ambition on emissions reduction and providing enough direction to give investment certainty while allowing industry the space to innovate. The CMP is clear that,

> **'Zero emissions shipping ambitions are intended to provide aspirational goals for the sector, not mandatory targets. They can only be achieved through collaboration between Government and industry, promoting the zero emission pathways that maximise the economic opportunities for the UK economy while also minimising costs for UK shipping.'**

UK government understands the significance of the offshore wind industry as a potential 'early adopter' of clean maritime innovation and sees potential benefit to industry, supply chain and the UK through the development of innovative solutions that can drive emissions reduction at the same time as stimulating growth in an emerging clean maritime industry of the future. Whilst the maritime emissions from offshore wind represent only a small fraction of total maritime emissions, it is an industry with a high level of commitment to improving sustainability through innovation and could lead the decarbonisation of maritime sector.

Government commissioned research estimates that the economic benefits to the UK across 11 key maritime emission reduction options could reach $650-890 million per year by the middle of the century [4]. The offshore wind industry, through its combination of market demand for clean maritime solutions and existing high UK content in maritime operations, is well placed to act as a 'springboard industry' to unleash the UK's potential for sustainable economic growth in this key future green industry.

There is great potential for the offshore wind sector to act as a 'springboard' to broader maritime decarbonisation, providing early adoption of technologies and market models. In recognition of this, the Department for Transport (DfT) and the Foreign, Commonwealth & Development Office (FCDO) commissioned ORE Catapult in partnership with the Workboat Association to develop a comprehensive innovation roadmap detailing how to decarbonise offshore wind vessels, with a particular focus on the North Sea.

The Roadmap aims to inform policy makers, industry and investors of the barriers to deployment so that security of investment increases and the risk of stranded assets is reduced.

ORE Catapult, in partnership with the Workboat Association, has undertaken research, including extensive industry and stakeholder engagement (Appendix 5) to help develop a Roadmap for the decarbonisation of maritime logistics in offshore wind.

The Roadmap aims to:A

- Provide a brief overview of the current landscape of the sector;
- Consider the likely growth scenarios in the sector for both installed offshore wind and associated vessels;
- Identify the main regulatory, technological and market risks for the decarbonisation of the sector’s maritime logistics;
- Identify the most efficient approaches to addressing the previously-identified risks, based on evidence;
- Identify the main currently available or high-to-medium TRL solutions;
- Develop a robust evidence-based route map with clear guidelines for industry, policy-makers and investors on how best to decarbonise the sector.

3 METHODOLOGY AND QUALITY ASSURANCE

3.1 Market scenariosA

The development of vessel growth modelling and proposed scenarios was conducted after investigating and analysing a variety of sources. ORE Catapult has experience of developing a number of business intelligence and market scenario tools which it maintains and updates on a constant basis to provide accurate estimations and insights for the organisation's market intelligence, stakeholder advisory work and for project delivery needs. The vessel growth scenarios were developed to provide estimations which will correspond to the net zero targets the government has set for the offshore wind and maritime sector.

The analysis completed an indepth literature review and uses data from a range of sources including, OSW industry stakeholders, UK governement databases, publicially available subscription sources and previous project outputs. Also, parts of the assumptions were built after leveraging our internal engineering expertise and cross-checked with parallel and closed relevant reports. Scenarios and forecast results were presented to industry during a series of five stakeholder workshops and feedback was invited from industry to help inform iterative updates to the draft model.

ORE Catapult has built projections of global offshore wind capacity by country up to 2050 which are updated regularly. This is sourced from subscribed databases ORE Catapult is a member of as well as observation of national energy targets each country announces. It is understandable that national energy targets usually tend to show increased ambition so may not always be in line with market projections. The latter take into account complexities and barriers for implementation so assessment of the available data is necessary to ascertain realistic scenarios.

Assumptions regarding the number of vessels required per windfarm are based on observations of the link between the current practices in offshore windfarms and the type of vessels and operating models used. In the future the number of turbines per MW will decrease, which should mean fewer transfers per windfarm, so this also suggests a reducing CTV requirement. On the other hand, a site probably has to be very small to operate with only a single vessel. Even for reasons of redundancy there is a preference to have the same number of CTVs as before to be able to react quickly in the event that a turbine requires unplanned maintenance, as every hour of downtime will come at considerable cost. CTVs and SOVs can also be utilised in combination where an SOV can also utilise a 'daughter craft', a type of CTV deployed from the 'mothership', allowing personnel to be rapidly transported around the wind farm for the more menial inspection and repair tasks. This concept has not been analysed in this study.

In addition, our sources of market insight suggest that there is trend for greater utilisation of SOVs with these vessels usually selected to conduct operations in windfarms at least 50km from shore. This information was used in combination with our projections for a trend towards increased distances from shore to turbine.

The pipeline of offshore wind projects in the North Sea is well defined up to 2027 based on an average seven-year timeline of projects from development to construction. In order to normalise the offshore capacity by 2030 to be in line with the realistic national energy targets assessed earlier, a number of 'placeholder' windfarm profiles were created reflecting market trends in distance to shore, turbine size and location. These profiles were then used to model assumed vessel logistic requirements which in turn have informed vessel numbers and power demand profiles associated with future operational wind farm fleets.

During the development of the numerical model used to inform the report's findings, a robust process was adhered to in order to provide quality assurance (QA). A table containing details of the approach to QA for the numerical modelling can be found in Appendix 1.

3.2 Industry engagement

In order to determine the key barriers to maritime decarbonisation a process of industry engagement was undertaken. This was done in order to elicit a better understanding of what real-world difficulties would be apparent in rolling out the technologies studied in Section 5.

Industry engagement was undertaken in 3 stages. Initially an online North Sea industry engagement event was held to gain a broad understanding of the views held across industry. This was then used to inform a questionnaire, designed to gain an in depth understanding of some of the barriers in more detail. This questionnaire was utilised in a series of one-to-one and small group interviews lasting around 1 hour 15 minutes each. Interviews captured the views of employees working in a wide array of roles in organisations large and small right across the sector. Interviewees were asked questions specific to their sector as well as being asked to voice their opinions as to how progress can be made in the sector as a whole. This data was captured both in the form of quantitative ranking of issues, short form answers to technical questions and open-ended questions designed to lead into discussion of whatever the interviewee felt was relevant. A process of thematic analysis was then undertaken to find common ground between the interview responses with key themes being identified. These key themes were then considered, with reference to the literature and input from in-house experts to devise a long list of barriers to decarbonisation. Refinement of these was them made during a series of industry panels. Barriers and ratings were presented to stakeholders from across 5 industry sectors in order to get feedback. Attendees were asked to vote on various aspects of what was presented, including: barriers missed; and barrier ratings they considered inaccurate. Following on from this was a discussion on what could be changed to ensure the findings reflected industry opinion.

Collectively, the stakeholders interviewed by ORE Catapult on behalf of the Department for Transport and the Foreign, Commonwealth & Development Office represent a significant proportion of operations in their respective sectors of the offshore wind industry, including offshore wind farm owner operators, port operators and vessel operators. Ørsted, Vattenfall, Siemens and Scottish Power operate 25 offshore wind farms in the North Sea, amounting to a total capacity of 9632 MW which accounts for over 50% of the total North Sea output. The port owner/operators interviewed also represent a major industry force. Combined, Associated British Ports, Port of Tyne, Amsterdam Ijmuiden Offshore Ports and Port of Oostende (REBO) currently cover the operations and maintenance on 23 fully commissioned offshore wind farms in the North Sea. Looking to the future, the mentioned port OO's are looking to service a further 6 wind farms that are currently under construction, putting the collective capacity of the 29 wind farms at 12,872 MW, accounting for 44% of the total North Sea output (Fully commissioned and under/pre construction). This means that the responses gathered can be considered to broadly reflect the views of the sector at large. As industry responses were analysed quantitatively as well as qualitatively the barriers listed should be treated with a reasonable degree of confidence but with an understanding that the final list of barriers has been compiled with a high degree of subjectivity. In order to provide quality assurance of these barriers, industry panels asked to give voting feedback as to how well barriers were assessed. Responses were positive, but where discrepancies were found these were used to refine the final list of barriers. More detail of the entire process can be found in Appendix 5.

4 VESSEL AND WIND FARM GROWTH SCENARIOS

4.1 Offshore Wind Deployment Growth ScenariosA

The UK is a world leader in offshore wind, with over 10 GW of operational offshore wind farms consisting of over 2,300 offshore wind turbines and plans to reach 40GW installed by 2030. Most of this capacity has been installed on the East Coast, the Irish Sea and English Channel. Scotland has about 1 GW of installed capacity. Floating wind provides an opportunity to exploit wind energy potential in deeper waters with demonstration floating wind farms already operational in Scotland. There is also a significant opportunity for floating wind deployment in the Celtic Sea estimated between 15-50GW.[A]

Germany is Europe's second largest market for offshore wind after the United Kingdom. Germany has a long history in onshore wind but offshore has only being developed in the last decade. The rapid growth led to a current installed capacity of about 7.5GW with ambitions to reach 20GW by 2030. France has no fully operational offshore wind farms installed in its waters but there is a target to reach 7.4GW by 2030 following a number of tender awards. The Government of Belgium aims to install 4 GW of offshore wind capacity by 2030, adding to six offshore wind farms that are fully operating in the Belgian North Sea. Denmark has currently similar offshore wind installed in its waters to Belgium but plans to add up to 7.2 GW of offshore wind capacity between 2027 and 2030. Norway has opened two areas for offshore wind development (4.5GW) and has plans for decarbonising its energy sector although no official offshore wind target exists yet. The Netherlands has a national target of a minimum 27% of energy consumption to come from renewable energy where offshore wind aims to play a key role reaching 11GW of installed capacity by 2030.

The national energy targets, decarbonisation policies, permitting regulations and cost of energy are key factors which define the scale of capacity acceleration. The lead time to develop offshore wind farms and grid connections is approximately seven years, so the pipeline of new projects expected to be installed by 2028 is relatively well defined. The high wind resource potential and the rapid growth of offshore wind installations in the countries around the North Sea will lead to an increase in demand for installation and O&M vessels in the next decade. Considering the above insights and based on ORE Catapult's global projections, two scenarios (base case and high case) were developed.

Both scenarios show identical capacity by the year 2025 where the pipeline of projects is already known and progressing. The base case scenario takes into account 64 new wind farms after 2025 whilst the high case considers an additional 20 wind farms, taking the total to 84 new wind farms after 2025 in order to meet ambitious national targets. Figure 4.1 shows the cumulative scenarios by country and by year up to 2030 for both cases.

Table 4-1: Base and High case scenarios of cumulative capacity in the North Sea countries.

Base case											
Cumulative capacity (MW)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Belgium	2,262	2,262	2,262	2,522	2,522	2,822	2,822	3,218	3,436	3,668	3,915
Denmark	1,878	2,483	2,643	3,307	4,029	4,229	4,449	4,689	4,949	5,229	5,529
France	11	11	551	2,111	3,057	3,057	3,057	3,752	4,611	5,556	6,596
Germany	7,644	7,644	7,989	8,246	8,973	10,773	12,421	14,346	16,464	18,793	21,355
Netherlands	2,640	3,023	3,793	5,263	5,263	5,263	5,873	6,573	7,773	9,173	10,673
Norway	2	6	95	105	105	455	601	1,101	1,801	2,801	3,711
United Kingdom	10,412	12,294	14,101	15,363	17,863	20,013	22,432	25,138	27,538	30,838	34,645
Total	24,850	27,723	31,434	36,917	41,813	46,613	51,656	58,818	66,573	76,059	86,425

High case											
Cumulative capacity (MW)	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Belgium	2,262	2,262	2,262	2,522	2,522	2,822	3,147	3,543	3,761	4,753	5,000
Denmark	1,878	2,483	2,643	3,307	4,029	4,229	4,449	5,131	5,391	6,700	7,000
France	11	11	551	2,111	3,057	3,057	3,057	3,752	5,313	6,258	8,000
Germany	7,644	7,644	7,989	8,246	8,973	10,773	12,968	15,440	18,287	21,527	25,000
Netherlands	2,640	3,023	3,793	5,263	5,263	5,263	6,455	7,155	9,169	10,569	13,000
Norway	2	6	95	105	105	455	601	1,101	2,590	3,590	4,500
United Kingdom	10,412	12,294	14,101	15,363	17,863	20,013	23,235	26,852	30,323	34,854	40,000
Total	24,850	27,723	31,434	36,917	41,813	46,613	53,913	62,973	74,834	88,252	102,501

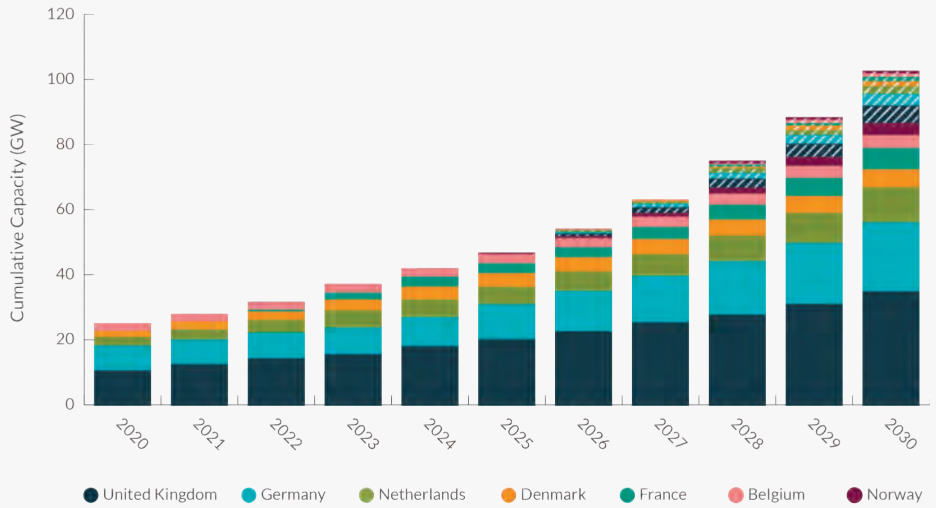


Figure 4.1: Deployment capacity scenarios, base case (solid colour) and high case (additional capacity in pattern fill).

The current cumulative capacity of North Sea countries is 24.8GW with projections to reach between 86.4GW and 101GW by 2030. Most of the operational wind farms are located in sites with shallow waters (<50m depth) and close to shore with 48% of total installations in 2020 being less than 25km from shore.

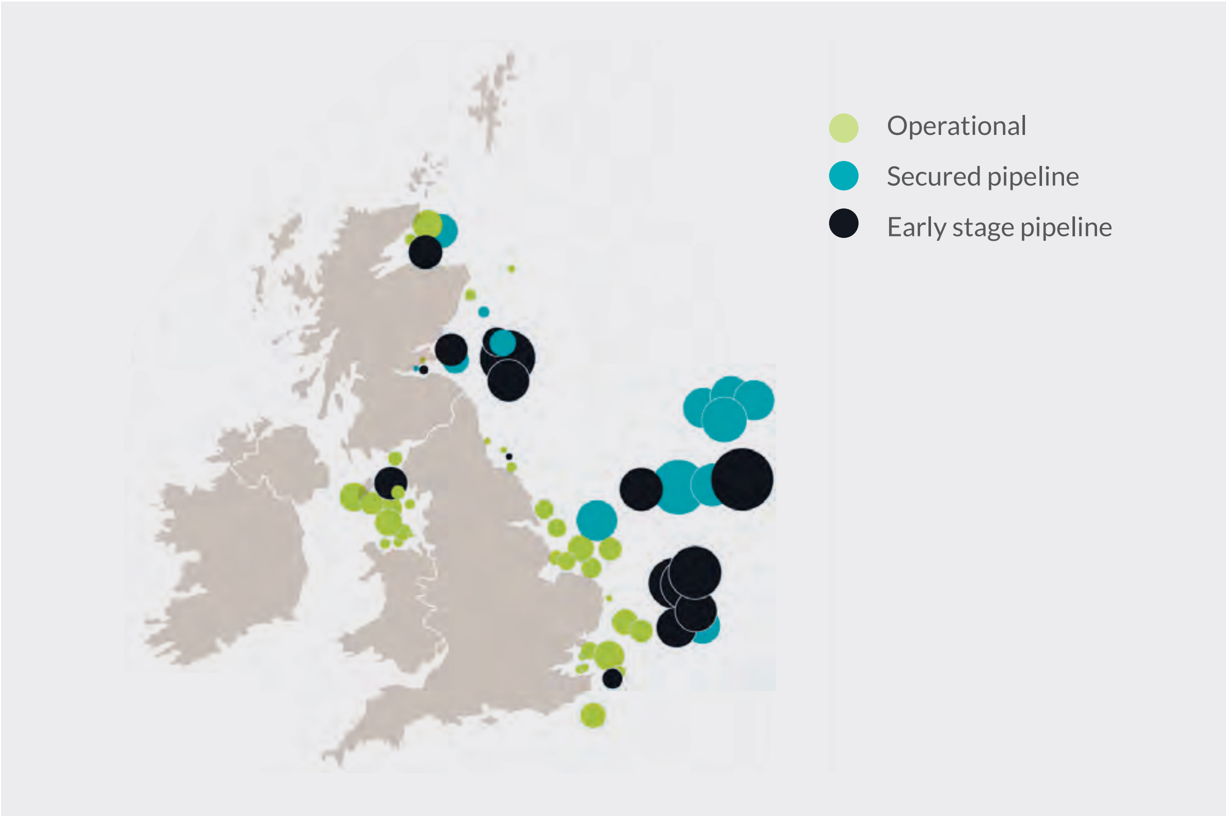


Figure 4.2: Operational and future UK wind farms [5] image courtesy of Wood Mackenzie (adapted).

North Sea sites show higher wind resource potential farther from shore, so wind farms currently in the pipeline up to 2030 are expected to be located on average in distances above 40km. Figure 4.3 expresses the above cumulative capacity in number of turbines installed based on the wind farm's distance to shore.

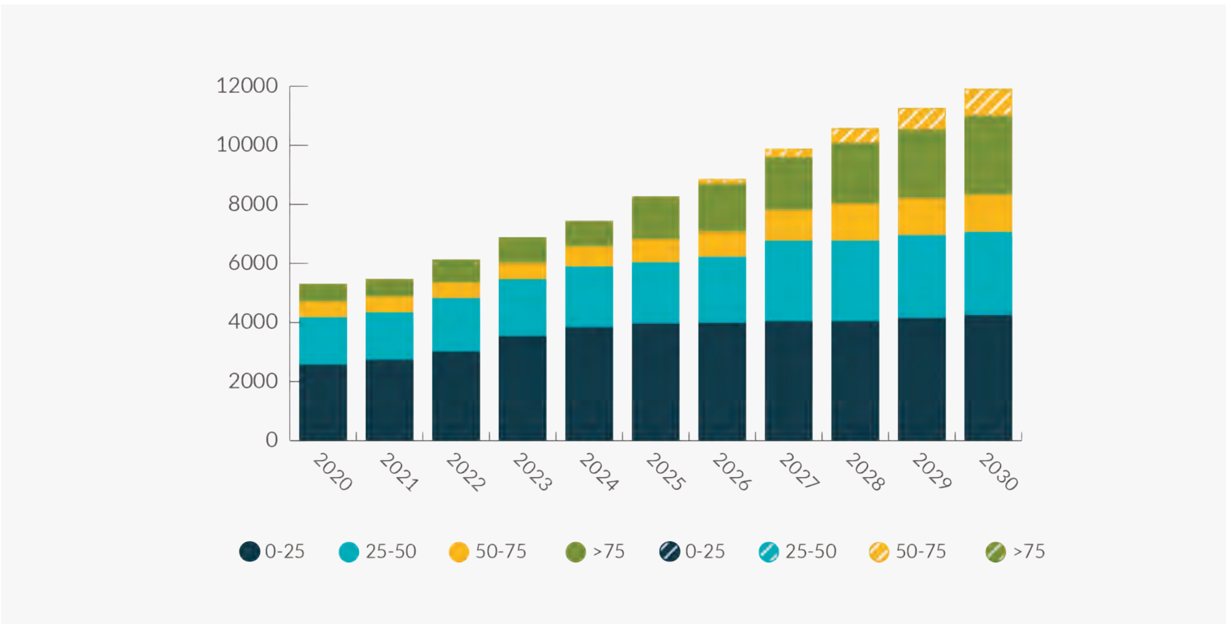


Figure 4.3: Cumulative number of turbines projections by distance from shore (km) in base case scenario (solid colour) and high case (additional units in pattern fill).

4.2 O&M Vessel Growth Scenarios

4.2.1 Methodology Overview

The forecast for wind farm installations indicates that construction and scheduled O&M activities will increase and therefore so will the demand for vessels in the next decades. Wind farm service vessels, mainly SOVs and CTVs, are built to serve offshore wind in construction and O&M phases. SOVs (Service Operation Vessels) are large vessels designed to be a platform for wind farm support, operating within the wind farm for weeks at a time. They house personnel and equipment and are usually deployed in wind farms further from the shore. CTVs (Crew Transfer Vessels) are smaller vessels used to transfer crew and small amounts of cargo between the shore and the windfarm.

The trend shows CTVs to be contracted less for construction work where SOVs take their place. For fully operational wind farms, over 90% of all vessels used for O&M activities are CTVs. As wind farm size increases and sites are located further from shore, SOVs will also become more common for O&M activities. Due to their larger size, accommodation and warehousing capability, better performance in harsh weather conditions and associated equipment suitable for offshore wind operations, SOVs naturally have longer endurance periods and tend to operate on 14-21 day rotations before needing to return to port.

The purpose of this analysis is to estimate the demand for O&M vessels in the North Sea countries based on their offshore wind deployment rate under different scenarios to measure and understand the size of the decarbonisation challenge in the offshore wind maritime sector by 2030. The focus of this analysis refers to minor repairs and preventative maintenance and does not include installation vessels. Installation Vessels represent a small proportion (approximately 46 currently active) of the offshore wind vessels, and their operation is limited to short periods of the wind farm lifetime (during installation, major repairs and decommissioning).[B] It should also be noted that an SOV can act as 'mothership' and utilise a CTV as 'daughter craft' allowing personnel to be rapidly transported around the wind farm for the more menial inspection and repair tasks. This concept has not been analysed in this study to avoid risk of double counting.

The scenarios developed assume that there is a strong correlation between the number of vessels hired and the number of wind turbines in respect to distances from port to site and between turbines. Limiting the transit time between port and site is important especially when CTVs are hired on a day rate and adverse weather conditions can increase the probability of seasickness. For this analysis a maximum of two hours transit from port to site is considered the upper limit for CTVs. For longer trips an offshore O&M accommodation base, usually an SOV, is recommended. In particular, for distances from shore below 50km we assumed no SOV. For distances above 50km, one SOV for every 700 MW can be hired.

SOVs spend most of their hours of operation on site at the windfarm rather than transiting from the operation base to site. For a 100-turbine wind farm 130 kilometres from shore, it is assumed that an SOV will be in transit just over half of the time with the remainder spent loitering for maintenance and repairs. 130 kilometres is higher than the average modelled in this report, therefore it is likely that this transit assumption is conservative, with loitering time higher in many cases.

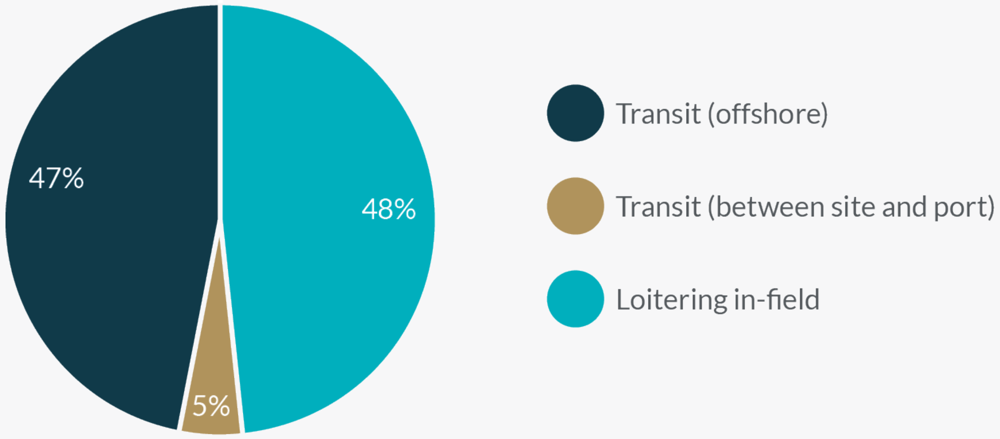


Figure 4.4: SOV annual usage for O&M activities in offshore wind[C].

The level of annual utilisation of the CTVs is closely related to vessel availability, contract type, seasonality and weather conditions. Based on historical data and market trends on utilisation level and size of CTVs, an average number of 3,700 hours of O&M operation per year was considered as representative for a CTV during the examined time period.[D,E] Bigger vessels usually show higher ability to withstand adverse weather therefore the CTV availability increases proportionally to the vessel length. However, the weather conditions generally become harsher as distance from shore increases so considering this trade off, operational hours were assumed to remain stable.

4.2.2 Methodology – O&M Vessel RequirementsA

On average four turbines are assumed to be repaired per trip with an average of one annual preventative repair per turbine and 20 annual calls for corrective maintenance. These rates have been defined from a combination of publicly available sources, particularly Carroll et al. and the SPARTA Portfolio Review 2016, as well as from the experience of the team at ORE Catapult.[F] The in-house COMPASS tool developed by ORE Catapult identifies the amount of time each vessel may spend idle at site (loitering). [6] The assumed fuel used for both vessel types in modeling is Marine Gas Oil (MGO) and different fuel consumption was taken into account for periods where vessels were in transit or idle on site (loitering). Table 4-2 shows the O&M assumptions from ORE Catapult's internal Levelised Cost of Electricity (LCOE) modelling and key specifications of the vessels. The annual transit time from port to site was calculated by year based on the distance to shore projections and can be found in Appendix 2. These assumptions were previously reviewed and validated as part of ORE Catapult's independent research by representatives from the Workboat Association, the University of Edinburgh and DNV.

Using the above assumptions, the number of turbines and O&M vessels were estimated by 2030 broken down by distance to shore and wind farm capacity. These were then multiplied by the annual time needed per transit (port to site and offshore) and per repair to estimate the total utilisation time by year. The hours estimated in combination with transit speed were used to calculate the total MGO fuel consumption and thus the total carbon emissions from O&M vessels.

Table 4-2: O&M vessel model assumptions.

Assumption	Unit	SOV	CTV
Transit Speed [G]	Knots	14	20
Transit offshore (between turbines)	km	10.0	17.5
Annual transit offshore	h	29.5	2.9
Annual maintenance usage per turbine	h	30.6	75.3
MGO for transit [H]	L/h	1,000	320
MGO on loitering 7	L/h	120	52[I,J]
MGO carbon emissions[K]	$kgCO_2e/L$	2.78	

4.2.3 Methodology – Decarbonisation ScenariosA

In terms of decarbonisation scenarios, the options of retrofitting existing vessels with battery hybrid propulsion and building new hydrogen fuelled vessels were modelled. The introduction of greener propulsion mechanisms and alternative fuels to new build and (where applicable) retrofit to existing O&M vessels will support the decarbonisation strategy of the sector and it is expected these types of vessels will become more prevalent in the next decade. The analysis estimates the O&M vessel operation time, the average fuel consumption and the associated CO_2 emissions by 2030 using a combination of scenarios (Table 4-3).

Table 4-3: Combinations of O&M vessels decarbonisation scenarios.

OSW deployment	Technology deployment	MGO price	Hydrogen price
Base case	Status quo	Low	Low
High case	Moderate	Central	Central
	Accelerated	High	High

4.2.4 Methodology – Technology Adoption Scenarios

The OSW deployment scenarios were described in the previous Section 3.1. Greener vessels are expected to become more widespread within the next decade either through battery retrofitting and use of transitional fuels like methanol mixed with diesel in dual fuel engines (70% carbon reduction) or operating with clean fuels like green hydrogen (100% clean). These solutions can have different speeds of adaptation so three technology deployment scenarios were developed to reflect the market share of each technology in the decade to 2030 (Figure 4.5). These scenarios depend on various enabling actions which are outlined in Section 7 of this report. Ammonia is not considered separately due to existing technical barriers in storage. Its source of production is not only from green hydrogen but also from conventional fuels which can produced in other countries and be imported.

Electric charging is considered a more realistic proposition from many in industry in the near-term although electric drive propulsion is broadly considered as viable only for CTVs and only for shorter journeys given current battery density and in the absence of offshore charging infrastructure. As such, lower carbon combustibles are generally seen as a more deployable proposition for larger vessels with higher endurance requirements. Nevertheless, it is important to note that there are CTV operators developing both electric drive and hydrogen fuelled concepts, whilst SOV designs commonly utilise electric hybrid systems.

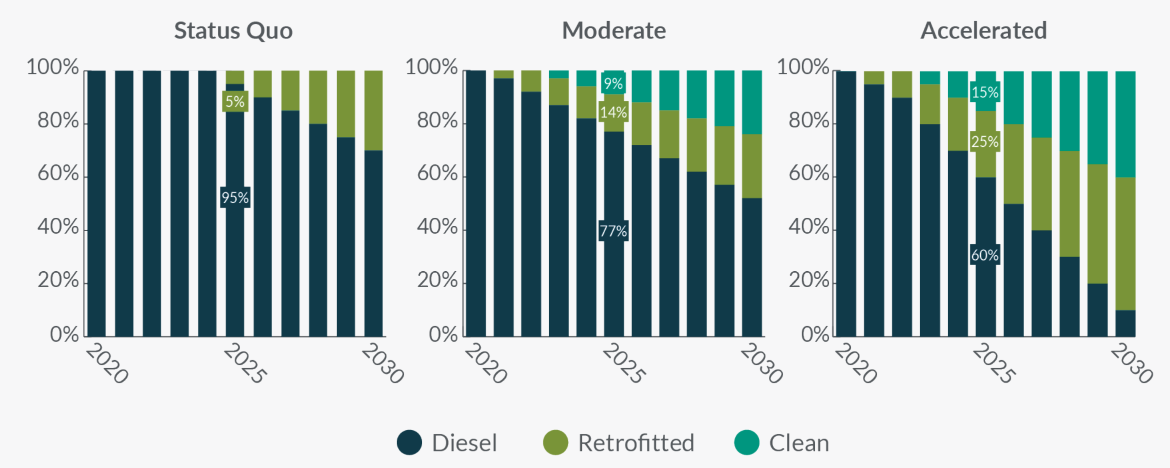


Figure 4.5: Green technology deployment scenarios.

4.2.5 Methodology – Fuel Price Scenarios

Fuel price scenarios are based on forecasts of existing reports from BEIS, BNEF and ORE Catapult's internal analysis (Figure 4.6).[L,M] Assumptions on energy density used to express fuel cost per MWh can be found in Appendix 2. In total the analysis produced 18 combinations of scenarios which helped to estimate the carbon emissions for SOVs and CTVs as well as their fuel cost by 2030. Fuel prices take into account efficiency of propulsion but not logistics of storage infrastructure due to the high uncertainty and complexities in their estimations.

In order to compare MGO and alternative fuels on the same basis, the analysis calculated MGO price at the refinery gate and the price of hydrogen at the production site gate. The price paid by vessel operators for MGO is approximately 60-80% higher than this (e.g. in 2020 the refinery gate price for MGO is estimated at 23p/litre, compared to 38p/litre paid by vessel operators at the port). The price vessel operators pay has been used in the analysis in Section 5.3. Understanding the premium paid by vessel operators between the alternative fuel (in this case hydrogen) production site, and the vessel loading, will be an important consideration for understanding the competitiveness of alternatives.

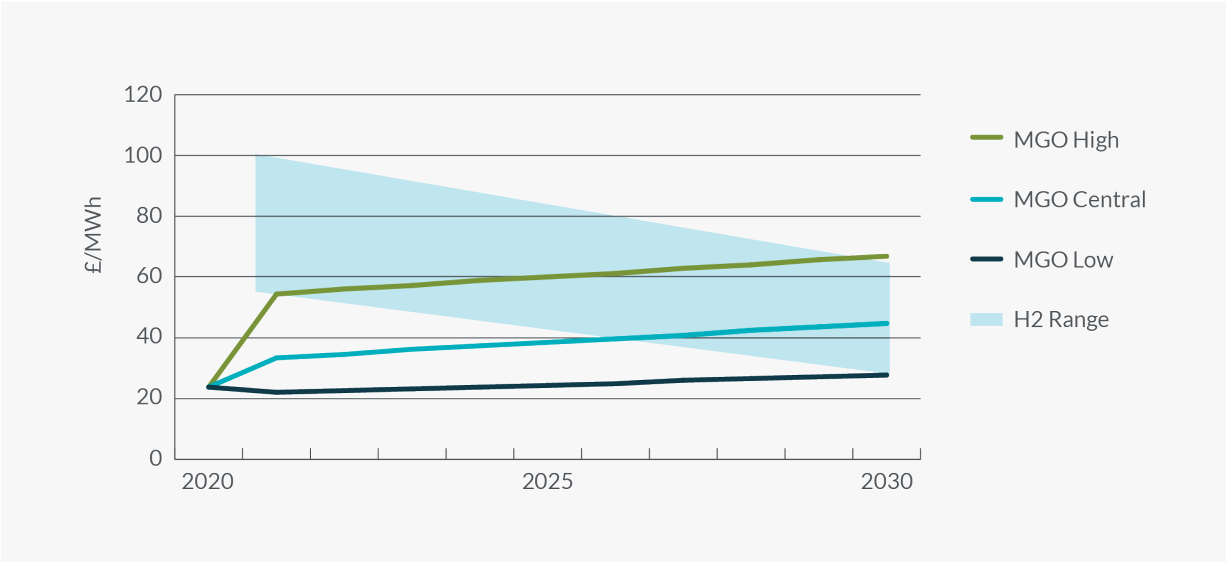


Figure 4.6: Marine gasoil (MGO) and hydrogen (H_2) fuel price scenarios[1].

4.2.6 Scenario ResultsA

The model estimations showed that by 2025, 249 O&M vessels will be needed to serve 166 offshore wind farms based on the current pipeline of projects. Differentiation of the scenarios starts after this year where in the base case scenario 389 O&M vessels will be required to conduct O&M work in 218 offshore wind farms of the North Sea in 2030. Approximately 75% of the total vessel demand will be for CTVs and 25% for SOVs. In the high case scenario, the total demand for O&M vessels can reach 455 vessels where 69% will be for CTVs and 31% for SOVs. The reason for the relatively low number of SOVs in both cases is due to the projection that the majority of the wind farms (approximately 64%) will be located close to shore in distances below 50km where an SOV is usually not necessary. In the high case, the additional wind farms are located on average 70km far from shore where SOVs are considered more suitable to conduct the O&M repairs. This higher average distance drives an increase of 43% for SOVs compared to the base case.

The status quo scenario represents a low level of adaptation to greener technologies with 95% of the vessels continuing to use conventional fuel by 2025 but after this point the rate is reduced slightly to 70% with only 30% retrofitted and no provision for clean fuel resources in 2030. In the moderate scenario one quarter of the vessels can be clean by 2025. In 2030 almost 50% of the vessels keep using fossil fuels and 50% can be retrofitted or being built to use hydrogen. Finally, in

1 MGO price for 2020 is provisional based on the central scenario of last updated BEIS crude oil forecasts published in 2019.

the accelerated scenario, one third of the vessels can use greener technologies by 2025 rising to 90% by 2030 in order to lead to almost full decarbonisation.

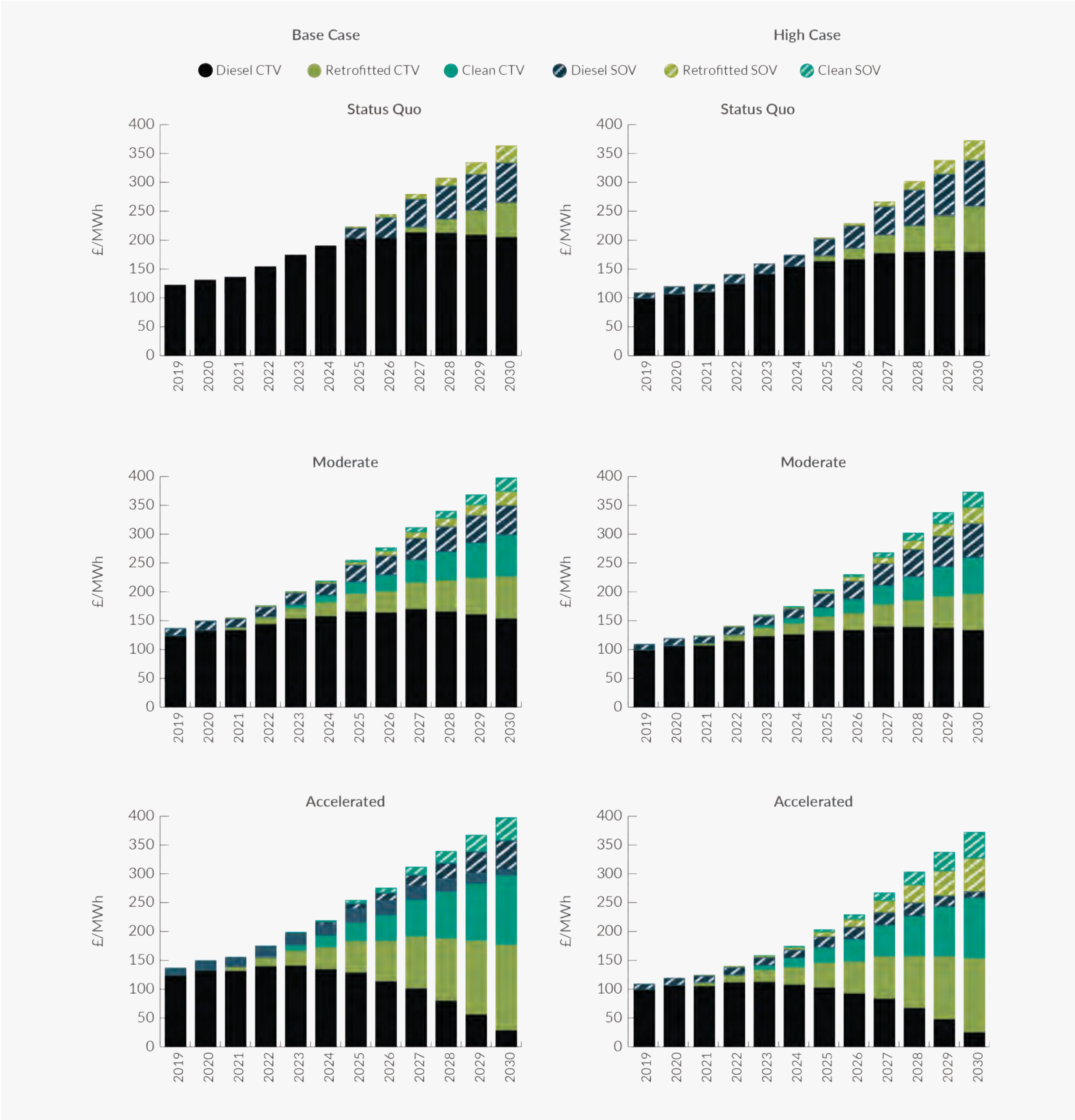


Figure 4.7: Projections on number of SOVs and CTVs broken down by fuel type and technology deployment rate for base case and high case North Sea offshore wind capacity scenarios.

Considering moderate fuel price projections, the estimation of carbon emissions showed, as expected, that the highest carbon saving between 2020 and 2030 can be achieved in high case accelerated scenario (3.91 $MtCO_2e$). Carbon can be reduced by 1.2 $MtCO_2e$ in 2030 (0.40$MtCO_2e$) compared to a benchmark case where all the O&M vessels will continue to run with MGO (Figure 4.8). On the other hand, the base case status quo resulted in the lowest carbon saving with only 0.71 $MtCO_2e$ in the next decade and 0.3 $MtCO_2e$ reduction in 2030 (0.95 $MtCO_2e$) compared to the benchmark.

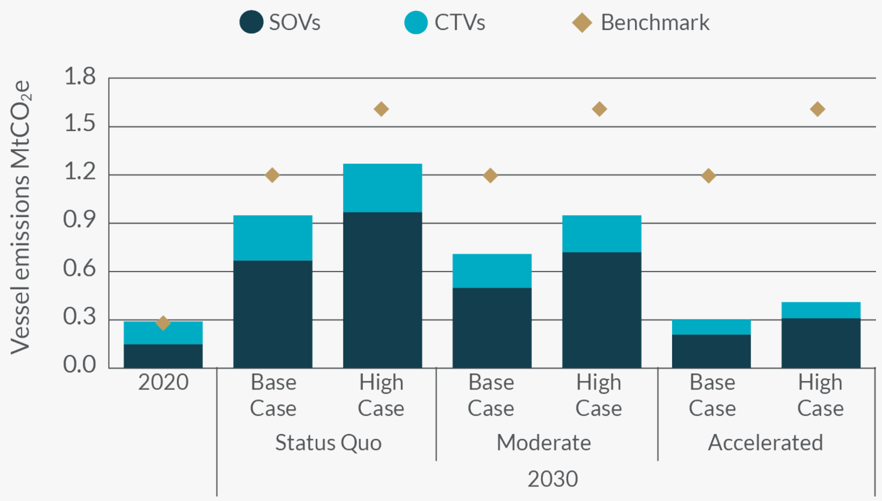


Figure 4.8: Carbon emissions scenarios for 2030 in comparison to an all MGO benchmark.

Apart from the environmental aspect, fuel cost is a key consideration on planning the most feasible decarbonisation strategy. Hydrogen price, as shown in Figure 4.6, is currently more than double the MGO price, however hydrogen has attracted strong interest globally with many countries structuring their net zero strategies around the integration of blue and green hydrogen. The ability of low carbon fuels to deliver energy and power densities comparable to traditional propulsion systems as well as the current lower efficiency of hydrogen fuel cells, the cost of storage, the fire risk with battery systems and the increased capital costs are recognised as major challenges by the industry.

Improvements in efficiency, overcoming technological barriers, economies of scale and public support can lead to a rapid cost reduction making H_2 price comparable to MGO by 2030 (£62/MWh). It is worth mentioning that H_2 may look far more favourable under a high MGO price, and low H_2 price scenario so in that case there will be no need for any carbon price to make it an attractive proposition. However, the cost of on-board storage is an additional factor which can determine how competitive H_2 can become compared to MGO. In the accelerated scenario where 40% of the O&M vessels can operate with H_2, the additional fuel cost can be over £90 million compared to an all MGO benchmark (Table 4-4). This implies that a carbon price of approximately £25 per tonne will be required to make a shift to H_2 attractive to O&M vessel operators.

Table 4-4: Fuel emission saving and fuel costs from 2020 to 2030 by scenario.

2020-2030		Base case			High case		
	Unit	**Status quo**	**Moderate**	**Accelerated**	**Status quo**	**Moderate**	**Accelerated**
Emissions reduction	$MtCO_2e$	(0.71)	(1.77)	(3.18)	(0.90)	(2.17)	(3.91)
Cost differential	£m	13.85	52.76	91.12	16.27	58.66	101.75
Implied carbon price	£/t	19.37	29.70	28.60	18.00	27.00	26.00

5 CURRENT LANDSCAPE OF INDUSTRY

5.1 Overview of Industry

Since the creation of the UK's first offshore wind farm, an E.ON demonstration project of two 2 MW Vestas wind turbines less than 2 km from shore in December 2000 [7], there has been a growing requirement on offshore vessels to support maritime operations throughout all lifecycle phases of wind farms.

Early approaches to crew transfer included rigid hull inflatable boats (ribs) being used to support the transit and transfer of technicians to offshore wind farms, followed by the use of retrofitted fishing vessels, which offered attractive minimum term contracts.

Since 2006, operators started moving away from these adapted vessel types to newly designed and built industry specific vessels. This allowed vessels to stay offshore for longer periods of time and in harsher sea conditions, as well as offering more comfort to the wind farm technicians and vessel crew.

By 2013, many of the easier to access, near shore sites had already been developed. Combined with change in the government policy, technology development and growth in the industry confidence, this led to the development of larger wind farms further offshore using higher rating wind turbines. Pressures to reduce costs and make offshore wind more affordable meant improved operating strategies were adopted. This drove demand for vessels with increased capacity and improve capability to access site in more adverse conditions. This, in turn, led to the development of larger CTVs and ultimately SOVs, an evolution of the OSVs (Offshore Service Vessel) commonly used in the Oil and Gas industry to meet offshore wind needs.

Historically, the industry has shown a tendency to favour larger and faster CTVs as a means of providing: transit for greater numbers of technicians (typically modern CTVs are 24 PAX); minimum time in transit; large cargo loading capacity; and safe transfer of technicians from vessel to turbine and vice-versa in higher sea states than would otherwise be possible.

Similarly industry preference tends to demand SOVs, that are as large as possible for the prospective ports and sea depths, that they are going to work in order to offer safe manoeuvring and transfer in otherwise challenging sea states; comfortable accommodation for large service teams (typically between 40-70 technicians) and optimal storage and warehousing capability.

In recent years there has been a gradual change in outlook to view more sustainable vessel types favourably, with most new CTVs and SOVs being designed and released currently having hybrid (electric and conventional fuel) technology incorporated into the design.

There are examples of demonstration and even some commercially operated vessels outside of the offshore wind industry using renewable and low carbon fuel sources. Nevertheless, these tend to be limited to certain industries and operational profiles which lend themselves to the technology types and the operational ranges that can be achieved currently on a commercially feasible basis.

Meanwhile, whilst many hybrid models of SOV and several hybrid CTV vessels have been deployed, there is, as yet, no evidence of zero emissions CTV or SOV having been commercially deployed in offshore wind operations.

5.2 Lifecycle of Offshore Wind Farm and Associated Vessels

There are several different vessel types that have very specific roles in the lifecycle of an offshore wind farm. A large number of vessels are deployed in offshore windfarms throughout their lifecycle [8], [9]. Table 5-1 provides a summary of these vessel types and which vessels are in the scope of this report.

Table 5-1: Commonly deployed vessels in offshore wind.

Lifecycle	Vessel type	In Scope of report
Development	Environmental Survey Vessels	
	Geotechnical Survey Vessels	
Installation	Offshore Cable Installation Vessel	
	Wind Turbine Installation Vessel (WTIV)[1]	
	Tugboats	
	Anchor Handling Vessel	
	Commissioning Vessels	
Operation and Maintenance	Crew Transfer Vessel	X
	Service Operation Vessel	X
	Large Component Repair Vessel	
	Tugboats	
	Anchor Handling Vessel	
Decommissioning	Offshore Cable Installation Vessel	
	Wind Turbine Installation Vessel	
	Commissioning Vessels	
	Tugboats	
	Anchor Handling Vessel	

Due to the high number of existing operational vessels and forecast increased future demand the emphasis of the study was placed on CTVs and SOVs. As these vessels operate in the O&M phases, which typically lasts between 25 and 30 years, decarbonisation of these vessels offers significant opportunities for accelerations and impact on clean maritime and associated technologies, both in bottom-fixed and floating wind.

Installation and large component repair vessels are not explicitly considered in this study as the evidence suggests that these vessels are unlikely to decarbonise within the timeframe of the study (2030). However, a number of technologies and fuels are considered that could be applicable to these vessels.

Floating wind specific vessels are not considered as part of this study, as the envisaged deployment of floating wind by 2030 will be very low (current government target of at least 1 GW) compared to bottom-fixed wind.

1 Wind Turbine Installation Vessel (WTIV) are typically self-elevating jack-up or floating heavy lift construction vessel.

5.3 O&M Vessels

In the following sections the main types of offshore wind O&M vessels are reviewed by considering the key structural and operation parameters. The emphasis of the review is on vessels providing routine maintenance and minor repair capabilities – CTVs and SOVs.

5.3.1 Crew Transfer Vessels

Crew transfer vessels are a commonly used means of transporting O&M personnel and materials to and from offshore wind turbines. CTVs are fast, manoeuvrable and are mostly used for transport to and from bottom-fixed wind farms close to shore. As CTVs are smaller in size than SOVs they face limitations with adverse weather conditions and have a lower max. operational significant wave height, resulting in less O&M opportunities throughout the year. Additionally, they have a smaller capacity to carry O&M personnel and materials, as well as a reduced range of operations from a port.

Up until 2017, CTVs had been limited to 12 PAX onboard. The introduction of the High Speed Offshore Service Craft Code in 2017 allowed CTVs to transport up to 24 PAX [10]. Between the code introduction in 2017 and the time of writing this report the percentage of 24 PAX CTVs have increased from around 4% of the CTV fleet to around 50% at present. This is expected to increase again in the coming years by retrofitting vessels built pre-2017 and designing new vessels to 24 PAX as operators continue to follow the trend of reducing O&M costs and improving wind farm operability.

5.3.1.1 Hull

The main CTV hull forms include [11]:

Table 5-2: CTV main hull types.

Type of vessel	Description	Significant wave height (m)	Image	
Monohull	The first type of CTV. Not purpose built for offshore wind, but rather retrofitted from other industries. Rarely used nowadays and account for around 4% of active vessels within the wind industry [12].	Approx. 1.5 m	CRC Voyager [13]	
Catamaran	The most commonly used type of CTVs. Typically built from aluminum. More expensive to build but potentially less expensive to operate compared to monohulls. Used in approximately 90% of active vessels within the wind industry [14].	Approx. 2 m	Aquata [12]	
Trimaran	A variation of the catamaran that has lower fuel consumption and improved seakeeping characteristics that allows personnel transfer to wind turbines in higher seas.	Approx. 2.5 m	World Boro [12]	

Type of vessel	Description	Significant wave height (m)	Image	
Small-Waterplane Area Twin Hull (SWATH)	Catamaran-like vessel but with smaller hull cross-sectional areas at the water level. This leads to greater stability, increased comfort, but at the expense of lower speed and increased vessel fabrication cost.	Approx. 2.5 m	MCS Swath 2 [12]	
Surface Effect Ship (SES)	A catamaran and hovercraft hybrid with good stability and seakeeping, low fuel consumption, but higher vessel cost.	Approx. 2.5 m	CWind Hybrid SES [15]	
Rigid Inflatable Boats (RIBs)	Smaller vessels that are generally used with SOVs or with fixed offshore base.		CRC Lodestar [12]	
Hydrofoil	Introduced in the last 5 years and used primarily for passenger comfort to aid with seasickness of technicians.		Artemis eFoiler [16]	

5.3.1.2 Propulsion

CTVs mainly use four types of propulsion systems:

Table 5-3: CTV propulsion types.

Type of Propulsion	Description	Popularity
Water Jet	This propulsion type offers higher speeds, shallow draft operations, noise reduction, increased maneuverability if used with a steerable nozzle, least efficient propulsion mechanism.	36% of active or under construction CTVs use Water-jet propulsion [12]
Fixed Pitch Propeller (FPP)	This propulsion type is the oldest and most basic form of mechanical propulsion that is most widely understood and with the lowest initial cost.	37% of active or under construction CTVs use FPP [12]
Forward Facing Propellers (FFP)	Forward facing counter rotating props pull the boat through the water rather than pushing it. It provides better fuel economy, better maneuverability, greater low speed handling and faster acceleration to traditional propeller driven engines.	6% of active or under construction CTVs use FPP [12]
Controllable Pitch Propeller (CPP)	This type of propulsion offers a higher propeller efficiency than with FPP, more efficient use of the diesel engine.	21% of active or under construction CTVs use CPP [12]

5.3.1.3 Engine, Generator and FuelA

The MTU 12 v 2000 M72 is a typical diesel generator used in CTVs (e.g. Seacat Freedom uses two of these engines). It is a 12 V-shaped cylinder arrangement engine. It is rated at 1,080 kW and weighs 2,780 kg (dry weight). In addition to the main engines, CTVs use auxiliary generators. Seacat Freedom uses two 19 kW auxiliary Cummins marine generators. Each weighs approximately 400 kg.

A study by the University of Strathclyde highlighted the following key O&M costs - charter cost, original equipment manufacturer cost, staff cost and fuel costs. Based on two CTV case studies against varying fleet sizes, fuel costs accounted 10-20% of the overall O&M costs [17].

To reduce the overall fuel consumption alternative lighter materials, such as glass reinforced plastic, have been considered for use in CTV construction. However, glass reinforced plastic is limited to CTVs that are 25-30 m in length. For larger CTVs, carbon reinforced plastic would need to be used to improve the strength characteristics of hulls, which would significantly increase the cost of the CTVs.

Fuel consumption, among other parameters, depends heavily on the vessel speed, weather criteria, operating profile, hull type, fouling on the hull, weight and propulsion system used. Typical values for CTVs are in the range of 100-500 litres per hour (e.g. 23-meter Windcat 40 vessel uses 360l/h at 31 knots and 250 l/h at 25 knots). Fuel consumption for auxiliary generators is typically two orders of magnitude smaller. Each Seacat Freedom auxiliary generator uses 2.5, 3.9, 5.2 and 6.6 litres per hours for 25%, 50%, 75% and 100% load, respectively. At the time of writing, the 2020 yearly average for marine diesel oil for commercial use is priced at approximately £0.4 per litre compared to the market cost of £0.23 per litre. It should be note that the price of diesel could have been affected by the Saudi and Russian price war and Covid-19 pandemic resulting in greater supply to the market, as pervious yearly averages tended to be around £0.8 per litre. It should also be noted at the time of writing that Duty and VAT are not applicable to marine diesel oil if the product is being consumed whilst on a "Marine Voyage".

5.3.1.4 Day Rate

CTV day rate is highly vessel dependent but typical day rates are between £1,000 to £3,000. Costs are affected by the length of the contract, what activity is being carried out and the demand for CTVs in the market at that time. This cost will include all personnel, insurance, taxes and maintenance of the vessel. However, fuel, water, electricity and berthing costs are usually excluded from the day rate and can vary from port to port. No single source is referenced as the question of charter rates is commercially sensitive. Nevertheless, the figures quoted here are based on conversations with multiple vessel operators, charterers and brokers.

5.3.1.5 Access Limits

Typical wind turbine access limits for catamaran CTVs are in the region of 1.5 – 2 m significant wave height. This is expected to increase to around 3 m significant wave height as next generation CTVs (e.g. tri SWATH) become available.

5.3.1.6 Fuel Consumptions

Distance covered by a CTV in a day is directly linked to the distance of the wind farm to the O&M base. However, distance covered by the same CTV in a year is a function of multiple variables, such as, size of the CTV fleet (i.e. utilisation of each CTV), size of the wind farm, weather conditions and asset failure rate.

Wind farm distance to shore and vessel length relationship is shown in Figure 5.1. Assuming that CTVs will be mainly limited to wind farms <60 km from shore (SOVs for 60+ km), an approximation for fuel consumption for a CTV in a year can be made and is presented in Table 5-4.

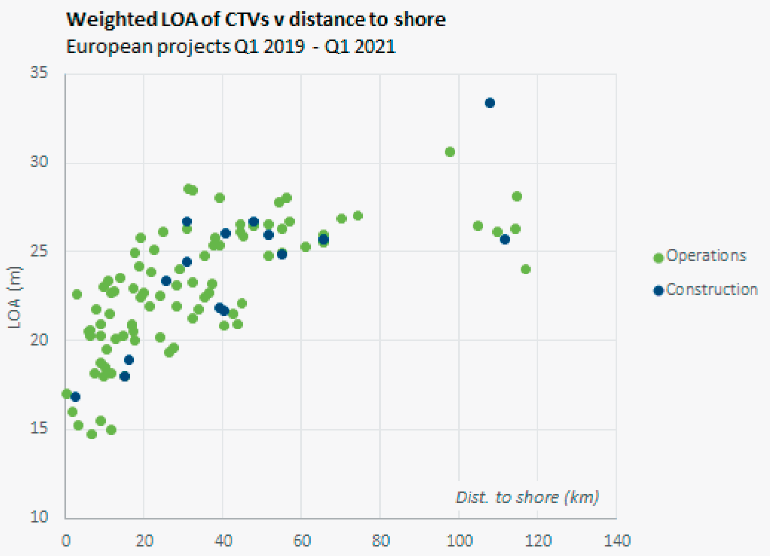


Figure 5.1: Overall length of CTVs used in O&M against Distance to shore. Picture courtesy of 4c offshore [12].

Table 5-4: CTV fuel consumption calculations.

Assumptions	Value
Distance to wind farm from O&M base (km)	40
Vessel type (-)	23 m length catamaran
Passengers (-)	12
Vessel transit speed (km/h)	40 (approx. 22 knots)
Vessel fuel consumption in transit (l/h)	320 [6]
Vessel fuel consumption in idling (l/h)	52 [18]
Idling time per trip (h)	8
Number of trips in a year (-)	200
Average Price of Commercial Fuel at Port in 2020 (£/l)	0.4
Results	Value
Number of transfers per year per CTV	4,800
Fuel usage (l/year/CTV)	211,200
Cost of fuel (£/year/CTV)	84,480

The highest fuel consumption rate occurs during open water transit to and from the site and technician transfer to and from the wind turbine.

5.3.1.7 Emissions

Fuel emissions for a CTV operating 10 hrs a day and 28 weeks a year with an annual fuel consumption of 211,200 l/year were calculated as 586.2 tonnes of CO_2 equivalent, 578.2 tonnes of CO_2, 7.8 tonnes of N2O and 0.1 tonnes of CH4. The methodology used to calculate emissions is provided in Appendix 3 all information used to calculate emissions has come from the Gov.UK Greenhouse Gas Reporting: conversion factors 2020 [19].

The auxiliary generators used in the UK must meet the Non-Road Mobile Machinery Emissions Regulation. The emission limits for auxiliary generators depend on the power rating of the generator. These can be looked-up in [20]. Emissions from auxiliary generators are significantly lower when compared to emissions from engines driven by lower power rating and consequently lower fuel consumption.

5.3.1.8 Case Studies

Provided in the table below are some examples of the best in class CTVs in operation or construction. These vessels make use of hybrid or the more efficient conventional propulsion systems to reduce their emissions.

Table 5-5: A number of best in class CTVs entering the market.

Name	Operator	Delivery Date	Hull	Engine	Propulsion	Crew and Passengers
HST Ella	HST Marine	01/Jul/2021	Catamaran	Hybrid propulsion of electric motor and diesel engine	Controlled Pitch Propellers (CPP)	4 Crew + 24 Passengers
Hydrocat 1	Windcat Workboats	01/Jun/2021	Catamaran	Hydrogen and Diesel	Controlled Pitch Propellers (CPP)	3 Crew + 24 Passengers
Manor Endurance	Manor Renewable Energy	28/Aug/2021	Catamaran	4 x 700hp Volvo Penta D13	IPS 900 (FFP)	4 Crew + 24 Passengers
Seacat Rainbow	Seacat Services	09/Nov/2020	Catamaran	Hybrid vessel main engine and battery bank	Water Jets	3 Crew + 26 Passengers
World Levante	World Marine Offshore	01/Sep/2020	Trimaran	Hybrid vessel main engine and battery bank	Water Jets	5 Crew + 24 Passengers

5.3.2 Service Operation Vessels

Service Operation Vessels (SOVs) are becoming more common within the offshore wind industry for carrying out O&M activities due to the increasing number of larger offshore wind farms and increasing distance of these from offshore. Originally SOVs came from other marine industries such as the Oil and Gas industry especially during downturns when SOV day rates were reduced to offshore wind rates for vessels to continue working. An SOV has several advantages over a CTV. For example, SOVs can stay in the field for much longer periods of time and operate in poorer weather conditions (i.e. increased significant wave height). The larger vessel also allows for a higher Person on Board (POB), better living conditions and smoother sailing. Newer vessels coming to the market are specifically being made for offshore wind activities and SOVs are equipped with active motion compensated personal transfer gangways (also known as Walk to Work (W2W) systems), cranes, increased storage capacity and in some cases helipads. Together, this allows for a higher number and increased complexity of O&M work to be carried out compared to other means.

5.3.2.1 Hulls

A number of different hull systems are currently used in SOVs with bulbous bow, X-bow and X-stern being the most widely utilised. These are discussed below in the order of least to most innovative and efficient.

In traditional straight bow ship designs, as the bow cuts through the water there is an increase in pressure and it produces a wave at the foremost point that runs along the side of the ship. As the surface area of water has increased with the hull this increases the drag and fuel consumption of the vessel. The bulbous bow is a hull design that reduces the size of the bow wave by creating a second bow wave that is out of phase with each other. If the bulbous bow is designed correctly and the waves are out of phase by 180 degrees, the result of the two waves is minimised and the drag is reduced.

Figure 5.2: Bulbous bow of a contaner ship by Danny Cornelissen.

The X-Bow was an innovative hull design from the Ulstein Group of Norway developed in 2006 and inspired by Viking longships. The backward sloping bow of the ship allows for the efficient volume distribution by increasing the fore ship volume of the vessel. The sharper angles of the X-bow design allow for the waves to be split and the forces distributed more effectively across the hull than traditional hull designs as shown in Figure 5.3.

Figure 5.3: X-BOW(r) on the The Service Operation Vessel 'WINDEA JULES VERNE'. Image courtesy of Ulstein Group/Tonje Øyehaug Ruud.

This X-Bow design offers several benefits to traditional hulls:

- Improved safety
- Reduced fuel consumption
- Less vibration and slamming caused by waves, which improves passenger comfort and reduces damage to the vessel
- Improved working environment
- Less noise and disturbance to environment
- Higher speeds in poor sea states

The X-Stern design is a hull design where the X-Bow is installed at the aft of the ship as well as the bow. This solution has been implemented from market research that shows 70% of in field operation occur backwards [21].

Figure 5.4: The Installation Support Vessel 'Acta Auriga', an Ulstein design including both the X-BOW® and the X-STERN®. Image Courtesy of Acta Marine/Coen de Jong [13].

Vessels carrying out infield operations working in reverse are down to a few of the following reasons:

- Work is performed at the aft of a vessel as that is where the crane and loading area are located.
- There is more power located at the aft part of a vessel enabling it to be positioned more effectively as well as the ease for DP of the vessels at site.

5.3.2.2 Propulsion

Figure 5.5: Azimuth thrusters by Alfvanbeem/ CC0 1.0.

Azimuth Thrusters

Azimuth thrusters are a common propulsion mechanism for SOVs. The propeller rotates 360 degrees around its axis allowing the vessel to steer and position itself without the need for a rudder. Retractable azimuth thrusters are also used on the underside of the hull at the bow to assist with positioning and turning a vessel during manoeuvres.

Figure 5.6: Maneuvering thrusters by Dr. Hochhaus/CC BY 3.0.

Manoeuvring Thrusters

Manoeuvring thrusters can be located in the bow or stern of a ship below the waterline. Generally, in offshore wind SOV design tunnel thrusters are used, however they can be designed with retractable thrusters as well. These thrusters allow for more accurate manoeuvrability when in field and allows the ship to dock in ports without the assistance of other vessels.

Figure 5.7: Voith Schneider propeller by Voith AG, Heidenheim.

Voith Schneider Propeller (VSP)

The VSP is designed to offer steering and propulsion in one unit. A circular disk with movable and controllable blades installed at a 90-degree angle to the disk rotates at the vessel bottom, this allows the magnitude and direction of thrust to be determined and controlled in real time and precisely.

5.3.2.3 Engine and Fuel

Purpose-built SOVs for offshore wind typically utilise diesel-electric hybrid propulsion systems. Damen has designed an SOV that utilises four gensets with the total rating of 6,434 kW (2 x Caterpillar 3516, 2,265 kW and 2 Caterpillar C32 952 kW). This is similar to the Esvagt Froude SOV that has the total power rating of 6,600 kW (4 x 1,650 kW). Each Caterpillar 3516 and C32 genset is approximately 7,050 and 4,270 mm in length, 2,570 and 2,010 mm in width, 3,020 and 2,170 mm in height and 20,000 and 6,700 kg in weight, respectively [22], [23].

Gensets are often supplemented with a clean emissions module to meet emission standards. The clean emissions module for the 3516 genset weighs approximately 1,400 kg and measures approximately 2,800 m in length, 1,650 mm in width and 925 mm in height. The combined weight of the genset system is over 55 tonnes.

Fuel consumption for a single Caterpillar 3516 marine genset is approximately 600, 450, 325 and 200 litres per hour at 100, 75, 50 and 25% load, respectively [22]. Fuel consumption for a smaller diesel generator Caterpillar C32 is approximately 250, 200, 130 and 80 litres per hour at 100, 75, 50 and 25% load, respectively [23].

SOVs typically use 1000 PPM Marine Gas Oil (MGO) ISO8217 Low Sulphur as SOV operations tend to be within restricted sulphur zones. At the time of writing, the 2020 yearly average for marine diesel oil for commercial use is priced at approximately £0.4 per litre compared to the market cost of £0.23 per litre.

5.3.2.4 Day RateA

There are a number of variables for the cost of a SOV such as vessel demand, fuel prices and length of contract (single/multiyear charter). After engaging with vessel operators and brokers, a range of £20,000-£27,000 per day for the hire of an SOV (including fuel and crew) is considered to be an accurate estimate at the time of this report being written. Prices fluctuate with demand and changes in fuel prices and have been as high as £45,000 for a spot hire in the last 5 years. Spot charter prices are expected to increase in the summer of 2021 as demand rises for SOVs to support inspection, maintenance and repair campaign work that was deferred during 2020 due to Covid-19.

5.3.2.5 Access Limits

Typical wind turbine access limits for SOVs are between 2 m and 3.5 m significant wave height, though heave compensated gangways are often rated to even higher wave heights. The number is mainly dependent on the vessel properties (e.g. size, type of dynamic positioning system used) and access technology used (e.g. walk-to-work, transfer boats).

5.3.2.6 Fuel Consumption

Range and hence fuel used up by an SOV depends on various factors, such as SOV's characteristics, distance from the base to the wind farm, environmental conditions, size and layout of wind farm, wind turbine failure rate.

SOVs are expected to be the choice of vessel for wind farms that are far offshore (50+ km). An example is shown below where a charter of 16 weeks is used. A number of assumptions were made including a crew change every 2 weeks with the SOV traveling half the distance to shore to change personnel (met half way by a CTV or alternative vessel) and than every 4 weeks the vessel returns to port to change crew and replenish stock and fuel. This leaves over 100 days where the SOV is in field at a reduced rate of fuel consumption. The assumptions and the results are presented in Table 5-6.

Table 5-6: SOV fuel consumption calculations.

Assumptions	Value
Distance to wind farm from O&M base (km)	100
Vessel type (-)	70 m in length
Vessel transit speed (km/h)	20 (approx. 11 knots)
Vessel fuel consumption in transit (l/h)	1,000 [6]
Fuel consumption - Infield (l/h)	120 [6]
Technician shift length (weeks)	2
Distance travelled to O&M base for a shift change (km)	halfway (50 km from base)
Stock replenishment frequency (weeks)	4
Charter length (weeks)	16
Average Price of Commercial Fuel at Port in 2020 (£/l)	0.4
Results	Value
Fuel usage (l/charter/SOV)	375,360
Cost of fuel (£/charter/SOV)	150,144

5.3.2.7 Emissions

Fuel emissions for an SOV with fuel consumption of 375,360 l/charter were calculated as 1,041.8 tonnes of CO_2 equivalent, 1,027.7 tonnes of CO_2, 13.8 tonnes of N_2O and 0.3 tonnes of CH_4. The methodology used to calculate emissions is provided in Appendix 3. All information used to calculate emissions has come from the Gov.UK Greenhouse Gas Reporting: conversion factors 2020 [19].

5.3.2.8 Case Studies

The following table details a number of SOVs presently operating in the market or under construction, along with the clients/projects they are allocated to and their charter durations.

Table 5-7: A number of SOV's on and entering the market.

Name	Operator	Delivery Date	Max Length x Beam (m)	Max Speed (knots)	Engine	Propulsion	Crew and Passengers
Acta Orion	Acta marine	2015	108 x 16	12	4 x 1,200 kW 800 kW 150 kW (emergency)	Stern 2 x 1,500 kW Bow 2 x 750 kW, 485 kW	25 Crew+ 55 Passengers
Esvagt Faraday	Esvagt A/S	2015	83.7 x 17.6	14	4 x 2,400 kW (3516C-HD diesel)	Siemens' BlueDrive™ propulsion system 2 x 1,600 kW	20 Crew + 40 Passengers
Esvagt Froude	Esvagt A/S	2015	83.7 x 17.9	14	Caterpillar diesel electric, 4 x 1,650 kW Siemens	Siemens' BlueDrive™ propulsion system 2 x 1,600 kW	20 Crew + 40 Passengers
Moray East	Esvagt A/S	2021	70.5 x 16.6	12	Unknown	Thrusters 2 x 1,100 kW	60 Berths
Wind of Hope	Louis Dreyfus Armateurs	2021	83 x 19.4	12.5	Diesel Electric - Main gen set: 1 x 300 kW @ 0-1,000 rpm	2 x Azimuth Propulsion Unit 1,660 kW, 2 x 1,400 kW transverse thrusters, 800 kW retractable	30 Crew + 60 Passengers

5.3.3 SOV Daughter CraftA

SOV daughter craft are frequently used alongside SOVs to complement them in the field. The daughter craft have room for around 8 – 12 PAX and started out as single engine ribs with a cabin on top but now include purpose-built fiberglass and aluminium vessels (see case studies below). The daughter craft will work alongside SOVs, offering transport to and from the wind turbines for technicians. It is particularly useful in cases when rapid response is required that SOVs are unable to provide due to their size and reduced manoeuvrability.

Daughter Craft are limited to 10 nautical miles from their safe haven, which could be a port or in many cases the SOV they are working with. As they are single engine craft and lighter than their CTV counterparts the rate of fuel consumption could be as little as a 25-50% [24] of that of a CTV and much less than a SOV. For example, Sea Puffin uses 150 l/h.

The smaller, agile and dynamic crafts are limited in operational range from a safe haven, making them prime candidates for full electrification with the potential for them to be charged at SOVs.

Table 5-8: A number of SOV daughter craft examples.

Name	PAX	Propulsion	Engines	Cruising Speed	Significant Wave Height	Payload	Length	Beam
Sea Puffin [24]	9 – 12	Water Jets	2 x 260 kW	20-25 kts	1.8 m	2 ton	15-16 m	5.6 m
Tuco Marine 1 [12]	8	Water Jets	2 x inboard	30 kts	1.5 m	1.5 ton	13 m	3.85 m
ProZero 15m [25]	12	2 x IPS	2 x Volvo Penta	25 kts	-	3 ton	14.8 m	3.85 m
ALUSAFE 1150 WF [12]	8	2 x IPS	2 x Volvo Penta	34 kts	2.5 m	1 ton	11.8 m	3.6 m

5.3.4 Overview

The following table summarises the key different technologies and operational parameters for CTVs and SOVs that have been covered in the sections above.

Table 5-9: CTV and SOV summary table.

Technology	CTVs	SOV
Hull Type	Monohull, Catamaran, Trimaran, RIBs, Surface Effect Ships, SWATHs, Tri SWATHs, Daughter Crafts	Bulbous Bow, X-Bow, X-Stern
Propulsion Types	Active Foils, Fixed Pitch Propeller, Forward Facing Propeller, Controllable Pitch Propeller	Azimuth Thrusters, Maneuvering Thrusters, Voith Schneider Propellers
Engine	~2,000 kW	~6,000 – 7,000 kW
Fuel Consumptions	~320 l/h (transit), ~50 l/h (idle)	~1000 t/h (transit), ~120 l/h (in field)
Day rate	£1,000 – 3,000/day	£20,000 – £27,000/day (up to £40,000+/ day on spot market)
Access Limit	1.5 – 2 m (Hs)	2 – 3.5 m (Hs)
Max. Days Offshore	1 (operating from port)	Up to 4 weeks
PAX	Up to 24	~60

5.4 New Technologies on the Horizon

5.4.1 Different Propulsion Types

In 2019 the Department for Transport carried out a review and assessment on the future low to zero emission technologies for shipping [26].

The report identified potential 38 technologies which were then shortlisted down to 11 that met the following criteria:

- Potential to make an impact on shipping emissions by 2050.
- Potential to be cost effective.
- Availability of date.

The shortlisted technologies have been used as a basis for this study and are discussed below but reviewed from the perspective of their relevance to offshore wind service vessels (CTVs and SOVs) and assessed in terms of their ability to be adopted commercially by 2030.

5.4.2 Hydrogen Production Technologies

5.4.2.1 Production

Hydrogen is one of the most common elements on earth, but rarely found in its pure form. It can be extracted from its compound (e.g. by splitting water) using any primary source of energy.

Different colours are used to distinguish between different sources of hydrogen production. "Black", "grey" or "brown" refer to the production of hydrogen from coal, natural gas and lignite respectively. "Blue" is used for the production of hydrogen from fossil fuels with carbon emissions reduced using CCS. "Green" is a term applied to production of hydrogen from renewable electricity, using electrolysis. Electrolysis is a process where water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) gas with energy input. Green hydrogen can be also produced from biomass gasification.

When combusted, hydrogen can be used to produce electrical energy from its chemical energy i.e. HFC which does not produce GHG's. Hydrogen emissions are significantly reduced (some NO_x and SO_x particulates) with the main 'waste' being water as opposed to CO_2 when compared to traditional hydrocarbon fuels. This has made hydrogen very attractive as a potential green fuel source.

Table 5-10: Hydrogen production methods.

	Term	Electricity Source/ Feedstock	Technology Employed	Emissions	Other terms used
Electricity Based H_2	**Green/ Renewable**	Wind/Solar/ Hydropower	Water Electrolysis	None	Clean Zero Carbon Carbon-Neutral H_2
	Purple/Pink	Nuclear		None[2]	
Fossil Fuels Based H_2	**Blue**	Natural Gas/Coal	Natural Gas Reforming/ Gasification + CCUS	Low CO_2 emissions	Low Carbon
	Grey	Natural Gas	Natural Gas Reforming	Medium	
	Brown	Brown Coal	Gasification	High	
	Black	Black Coal	Gasification	High	

5.4.2.2 Case Studies

Case study

ERM Dolphyn (Deepwater Offshore Local Production of HYdrogeN)

ERM Dolphyn (Deepwater Offshore Local Production of HYdrogeN) is a R&D green hydrogen production project that will be trailed at the Kincardine Floating Wind Project 15 km off the coast of Aberdeen, Scotland. The plan is to deploy a 2 MW wind turbine and electrolyser prototype system that will use renewable wind power to create electricity from water pumped from the sea and distilled before being fed into an electrolyser to create hydrogen that is pumped back to the shore from 2024. The ambition is to scale this 2 MW prototype up to a 10 MW turbine by 2027.

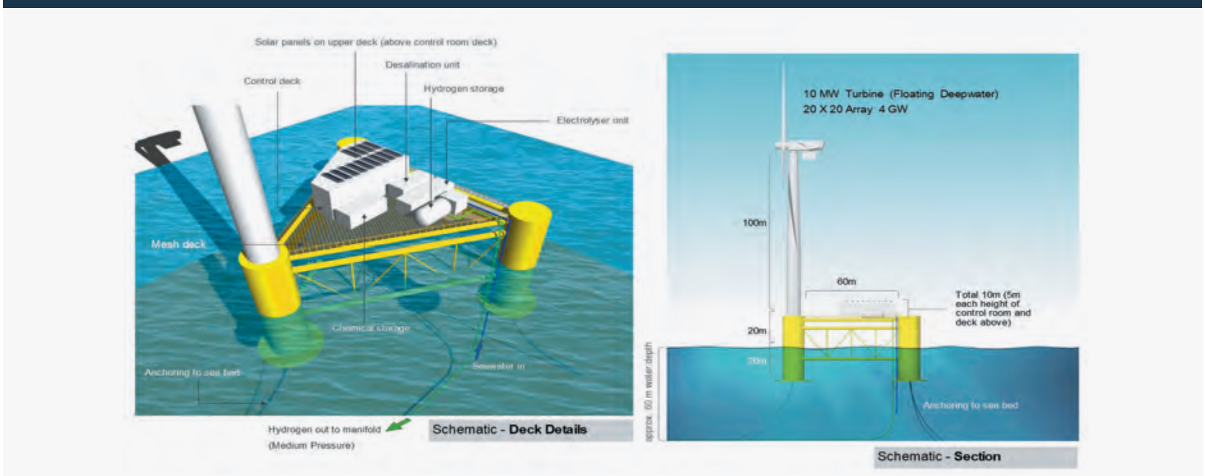


Figure 5.8: ERM DOLPHYN hydrogen project foundation and electrolyser [27]. Image courtesy of ERM.

2 Nuclear waste

Case study

The PosHYdon Hydrogen Pilot

The PosHYdon Hydrogen Pilot is the world's first offshore green hydrogen production project [28]. The pilot is on the Q13-A platform operated by Neptune Energy in the Dutch North Sea and produces hydrogen using demineralised sea water from excess green electricity. Hydrogen is then pumped, blended and integrated into the existing gas pipeline. Initially this electricity will be powered from green resources onshore but in the future, it could be powered directly from offshore wind turbines. The small hydrogen production unit as shown in Figure 5.9.

Figure 5.9: Poshydon' hydrogen production platform by Neptune Energy [28].

Tractebel, which is part of the Engie Group, have developed an electrolyser, desalination plant and transformer that can transform excess green electricity created by offshore wind turbines into hydrogen. The concept design can deliver up to 400 MW and looks to be installed on purpose built platforms or possibly utilising existing O&G infrastructure. Hydrogen can then be transferred to shore via pipeline or vessels. It is anticipated that the first platforms could be installed as early as 2025 [29].

There are currently a few challenges that need to be overcome if hydrogen is to replace hydrocarbons as our primary source for energy. Hydrogen has a low energy content by volume compared to hydrocarbons requiring either large volumes, high pressures or low temperatures for increased density storage. Additionally, green hydrogen is currently more expensive than grey hydrogen or conventional fuels [30], the former costs between $3-7.5/kg comparing to $1-3/kg for grey.

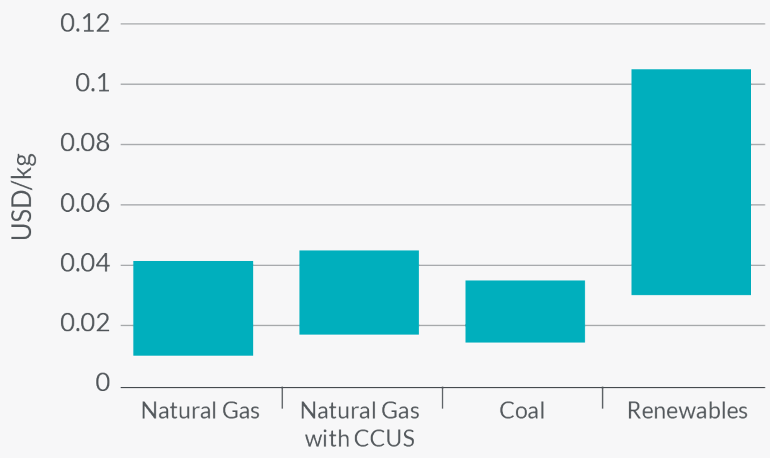


Figure 5.10: Cost of hydrogen per kg as of 2018. Source data: IEA/All rights reserved [30].

Nevertheless, numerous reports have concluded that green hydrogen production may achieve cost parity with fossil fuel-based hydrogen by 2030-2040 [31] [32]. The speed of cost reduction is dependent on accelerated deployment, reduction of renewable electricity cost, equipment costs and electrolyser efficiency.

Offshore wind and Hydrogen: Solving the Integration Challenge report by ORE Catapult highlights that with the increased scale of green hydrogen production, lower cost of renewable electricity and more standardised manufacturing processes costs are forecast to fall by 60% in the next 10 years [31]. A DNV GL study [33] has stated that green hydrogen could be affordable as early as 2035 due to 3 main reasons:

- The cost of electrolysers will go down – due to improved designs and standardised manufacturing practices.
- Periods of low cost price for electricity will increase – this is due to the increase in offshore wind production and surplus generation during low capacity time such as nights.
- Carbon Policies – the expected penalisation of carbon emissions by government policies in the coming years and industry and governments move away from this.

Some of these reasons are already being realised as UK company, ITM Power, announced plans for a 1 GW electrolyser plant in Sheffield, England which the manufacturer claims has the ability to cut the cost of electrolysers produced at the plant by around 40% over the next 3 years. This is due to increased automation and economies of scale [34].

5.4.2.3 Hydrogen usage (carbon free fuel)A

This report will look at three ways in which hydrogen can be used to power a vessel:

- Hydrogen combustion
- Hydrogen fuel cells
- Ammonia production

Hydrogen combustion engines have been developed around the design basis of their petrol and diesel counterparts. Hydrogen combusts with oxygen in the atmosphere and the explosion can be used to move pistons in the same way as a petrol or diesel engine. This allows hydrogen to be combined with conventional fuels and used with little alterations to currently operational diesel engines. The main by-product of burning pure hydrogen is water with some NO_x and SO_x, providing a greener solution without any CO_2 being released in the reaction.

However, there are a number of challenges associated with the adoption of this technology for marine vessels. One of these is the relatively low energy density of hydrogen compared to petrol or diesel. This can be seen in Table 5-11 where there is nearly 4 times the distance covered by petrol compared to hydrogen with the same amount of fuel.

Table 5-11: Fuel consumption of BMW hydrogen 7.

Petrol (gasoline)		Hydrogen	
L per 100 km	Mpg	L per 100km	mpg
13.9	20.3 imperial 16.9 US	50.0	5.6 imperial 4.7 US

This results in a greater volume of hydrogen being required for the same about of energy. Hydrogen tanks would need to be bigger, as well as refrigerated to significantly lower temperatures or rated to high pressures to accommodate a greater volume of gas, which brings its own safety and engineering challenges.

Traditional internal combustion engines can theoretically recover a maximum of around 50% of the useful energy with the rest being lost as heat and sound. However, in practice, the recovered useful energy is significantly lower and varies from engine to engine.

Case Study

Windcat Hydrocat

Windcat Hydrocat is a CTV vessel being designed by Windcat Workboats. It is currently in manufacture and due to be in operation by late 2021. Vattenfall have signed a contract which will see the vessel operating in the Hollandse Kust Zuid 1 & 2 offshore wind farms in the Dutch North Sea. This project is located 22 km off the coast with the port of Ijmuiden being selected as the O&M base and is expected to be commissioning in 2022.

The Hydrocat looks to displace 80% of the diesel used in hydrocarbon only CTVs, with hydrogen reducing emissions by 80% with further reductions through a SCR system. The Hydrocat, with variable pitch propellers and a catamaran hull, will carry 24 passengers and 3 crew at a cruise speed of 25 kn and be propelled by 2 x 1,000 horsepower diesel and hydrogen engines which will consume 170 kg of hydrogen a day [35].

Figure 5.11: Windcat Hydrocat by Hydrocat.

Case Study

HyDIME (Hydrogen Diesel Injection in a Marine Environment)

HyDIME (Hydrogen Diesel Injection in a Marine Environment) is a UK based project funded by Innovate UK that plans to use hydrogen produced by green electricity from wind and tidal power to fuel a commercial ferry operating between Shapinsay and Kirkwall, Orkney. The plan is to retrofit an existing commercial passenger and vehicle ferry by designing and fitting a hydrogen injection system as well as the interface between the vessel and a dockside hydrogen storage solution. Once this has been achieved, the project will look at how the lessons learned can be used to scaled up operations and look at the impact and opportunities to replicate this design throughout the UK [36].

Figure 5.12: Commercial passenger and vehicle ferry in Orkney to be retrofitted for hydrogen suitability [36].

Case Study

Hydrogen Fuel Cells

Hydrogen fuel cells are an alternative to combustion as the hydrogen is used to power an electrochemical fuel cell that converts the chemical energy directly into electricity as detailed below in an ABB hydrogen fuel cell system (see Figure 5.13).

Fuel cells are an efficient way of converting chemical energy to electricity as there are no mechanical losses from heat and sound that are experienced in traditional combustion engines. This allows for more efficient conversion compared to hydrogen combustion, further reducing NO_x and SO_x emissions produced by internal combustion engines.

The key barrier for hydrogen fuel cell adoption in the industry is their relatively high costs, which currently cannot compete with conventional technologies. The cost is driven by use of expensive components like the membrane that is used to transfer the positively charged particles and is made from expensive metals such as platinum. Other challenges include the low energy density of hydrogen, but this can be overcome with pressurising the hydrogen at the inlet and reducing the inlet temperature. Fuel cells have a slow response time and in current test must be supplemented with batteries.

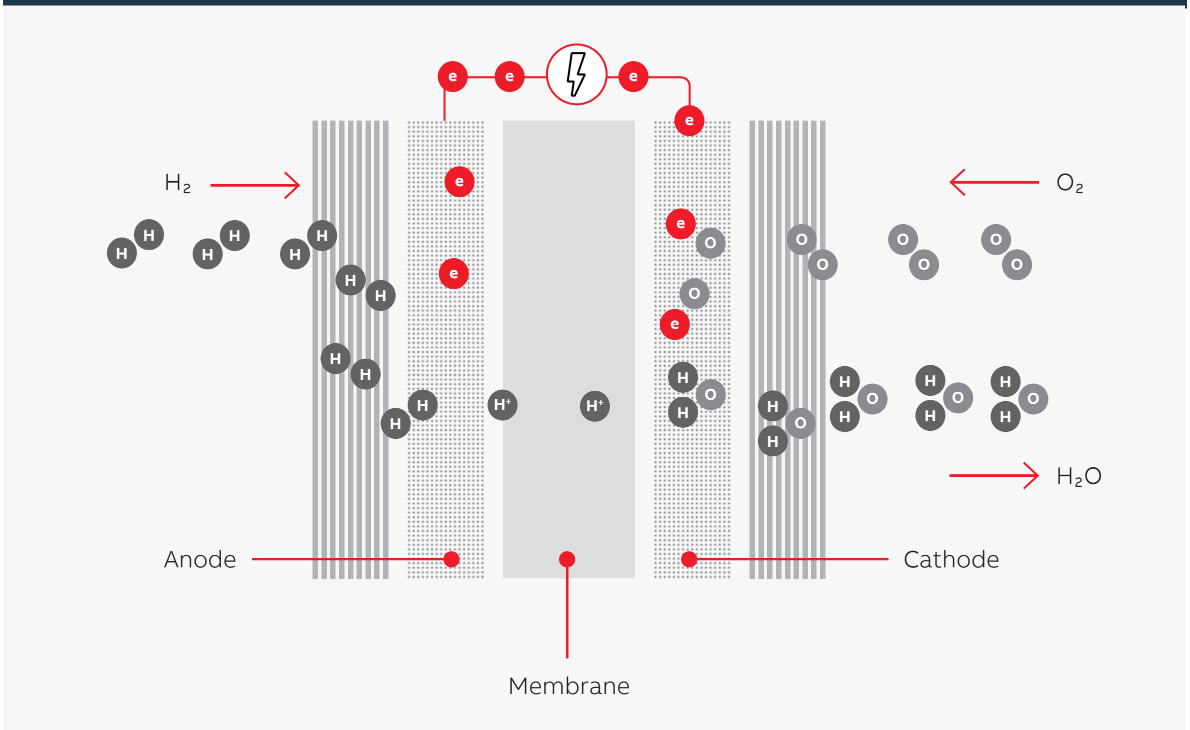


Figure 5.13: Fuel cell illustration by ABB [37].

Case Study

Havyard - Hydrogen fuel cell cruise ship

Currently the world's first liquid hydrogen fuel cell cruise ship is being designed by Havyard Design for shipowner Havila to be used in the Norwegian Fjords by 2023 [38]. A 3.2 MW fuel cell will be supplemented with battery storage to make the vessel emissions free. This will be in time for new legislation that will ban any vessel that is powered by hydrocarbons and emits CO2 from entering the Fjords from 2026. The fuel cells supplemented with battery storage will allow for higher speeds and longer distances that couldn't currently be supported by battery power alone.

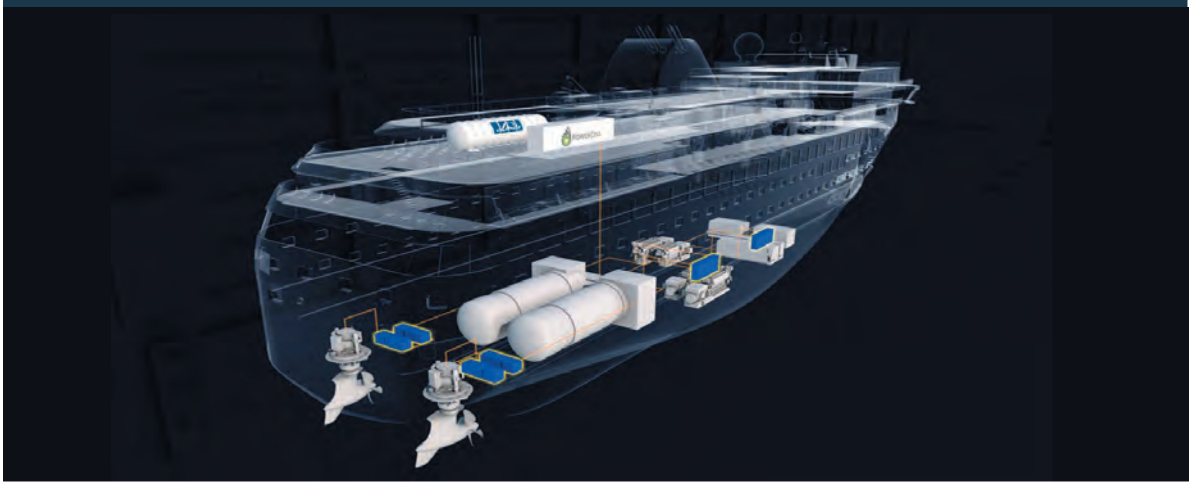


Figure 5.14: Havyard hydrogen fuel cell design [39]. Image courtesy of Havyard Group ASA.

Case Study

Piriou - Hydrogen fuel cell powered hybrid CTV

French Ship designers Piriou have unveiled plans for a new hydrogen fuel cell powered hybrid CTV. The CTV will be designed with two 1,000 kW main engines and two 140 kW fuel cells [40].

Figure 5.15: Piriou hybrid hydrogen fuel cell CTV [40].

Several companies have partnered to produce a green hydrogen fuel cell powered vessel to generate electricity. The DFDS' ferry sailing the Oslo – Frederikshavn – Copenhagen route will produce 23 MW of energy to power the vessel [41]. The current design of fuel cells is in the region of 1-5 MW, so the design is focusing on innovation to bring larger fuel cells to market. The ferry is planned to be operational in 2027 and will be called the Europa Seaways. It will be designed for 1,800 passengers and a combination of 120 lorries/380 cars forecasting to eliminate 64,000 tons of CO_2 per year.

Ammonia is a carbon-free molecule and when combusted produces only nitrogen and water. Ammonia can burn in an internal combustion engine. When comparing an ammonia powered internal combustion engine with a conventional one the technical performance is similar on power density, load response and part load performance but the conventional engine would have significantly higher emissions.

Similarly to hydrogen, ammonia can be produced in several ways and named 'green', 'blue' or 'grey'. Ammonia is conventionally produced from natural gas (grey), in the Haber Bosch process. By this route CO_2 is a by-product. The Haber-Bosch process is still the industrially applied process for ammonia synthesis. Ammonia becomes a carbon-neutral fuel when it is produced from renewable energy sources (green), or when it is produced using fossil fuels with carbon capture and storage technologies (blue). Renewable energy can be used to power a reverse fuel cell to make ammonia. The renewable hydrogen created by electrolysis can be combined with nitrogen filtered from the atmosphere.

Ammonia is a versatile product that can not only be used as a fuel, it can be used as a fertilizer, cleaning product, within refrigeration cycles as well as a method for transporting hydrogen at -34 °C as a liquid as opposed to liquid hydrogen at -253 °C, which can solve many transportation and storage challenges. Ammonia could then be cracked and released back to nitrogen and hydrogen that can be used as described above in an internal combustion engine or fuel cell.

Figure 5.16 compares hydrogen and ammonia, in various states, against other conventional carbon based fuels. Of the zero-carbon fuels shown in the figure, ammonia offer the highest volumetric density, both at low and ambient temperatures.

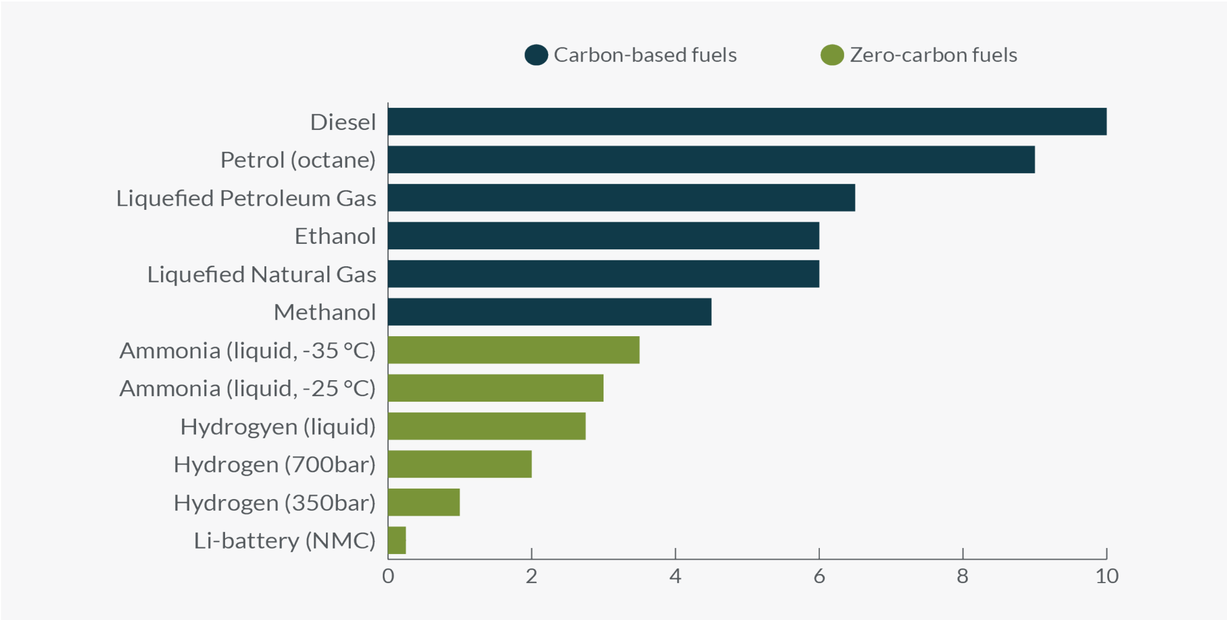


Figure 5.16: Volumetric energy density of a range of fuel options. Image courtesy of The Royal Society [42].

From the late 1920s until the 1990s ammonia was produced by Norsk Hydro in Norway using alkaline electrolysis and air separation powered by renewable hydropower and the Haber-Bosch process for the ammonia synthesis.

There are health and safety considerations to be factored into the usage of ammonia. Ammonia is corrosive to the skin, eyes and lungs and releases into the environment can be hazardous to marine life.

Case Study

Eidesvik - Viking Energy vessel

Operator Eidesvik is working on retrofitting the Viking Energy which is a service vessel working on Equinors offshore operations on the Norwegian continental shelf to be powered by ammonia fuel. Eidesviks plans are to install ammonia fuel cells with a total power of 2 MW and have the vessel ready for operation in 2024 [43]. The vessel will be able to operate for at least 3,000 hours annually on clean fuel.

Figure 5.17: The Viking Energy vessel [44].

Ørsted and Yara have joined forces to develop a 100 MW wind powered electrolyser plant for green hydrogen production, wind energy will be provided from Ørsted's Borssele 1&2 offshore wind farms. This green hydrogen is a key building block in ammonia production and is aimed for use in Yara's Sluiskil Plant in the Netherlands. The green hydrogen will replace the traditional methods of hydrogen production and remove 100,000 tonnes of CO_2 per year. The project is seeking the public co-funds and regulatory buy in and plans to be in operation for 2024/25 [45].

5.4.3 LNG (and Bio-LNG) Production TechnologiesA

LNG is a natural gas made up of a mixture of predominantly methane, ethane, propane and butane. The gas is chilled down to a liquid state (-162 °C) to increase its volumetric energy density by approximately 600 times. LNG can be stored at atmospheric pressures.

Bio-LNG is liquified biomethane created from processing organic waste such as animal or food waste. It is created when the waste is broken down by anaerobic digestion (broken-down without oxygen present) and the waste gasses that are released are collected. When biomethane is burned it produces harmful pollutant gasses such as SO_x and NO_x but at much lower quantities compared to diesel. Bio-LNG is classed as a low carbon fuel source.

LNG has been gaining acceptance as an alternative within the maritime industry. According to DNV-GL, in 2019 there were 163 LNG fuelled ships, with an additional 123 LNG ready ships and 83 are on order [46]

Hapag Lloyd is converting the Sajir, a large container ship, to LNG. The engines previously used HFO and will now have dual fuel capabilities, using LNG and low-sulphur fuel oil.

The world's largest car truck carrier to be solely powered by LNG is being built in Japan. The Sakura Leader is scheduled for delivery in 2021 and will be able to transport around 7,000 units per voyage [47]

Figure 5.18: The Sajir vessel [48].

Figure 5.19: The Sakura leader vessel [47].

5.4.4 Methanol Production Technologies

Methanol is a versatile chemical that can be used in many ways such as plastic manufacturing, paints, cosmetics and fuels. Global demand for methanol is expected to be approximately 130,000,000 tons annually by 2025 [49]. Methanol can be produced from fossil fuels, predominately created on an industrial scale from natural gas by reforming the gas with steam and then converting and distilling the resulting gas to methanol. There are also ways to create methanol from renewable sources such as combining hydrogen generated by electrolysis with CO_2 that could be captured before being emitted to the atmosphere. An alternative method involves fermenting biomass that produces synthetic gas that can be processed and formed into bio-methanol [50].

In operation, methanol offers significantly lower CO_2 emissions (up to 95% reduction) compared to conventional marine fuel, if produced from one of numerous renewable pathways. As a marine fuel, methanol is compliant with the IMO's 2020 regulations by reducing SO_x by approximately 99 % [70].

Methanol has been used as a fuel source in the marine environment for a few years now. At the time of this report being written the world's first commercial methanol powered ship celebrated 5 years in service. The Stena Germanica, a 240 meter long ferry, was retrofitted with a fuel-flexible engine that can run on methanol or traditional marine fuel in 2015. It is currently in operation sailing 1,500 passengers and 300 cars between Gothenburg in Sweden and Kiel in Germany [51].

The conversion of vessel engines to run on methanol requires new fuel injectors and fuel rail systems. With the fuel system being double walled and the use of nitrogen as an inert gas in the fuel tank to protect from leaks and ignition sources. These modifications are simpler to undertake than LNG conversions and this is the same for new build versions of both vessels [52]. Methanol is becoming a common fuel source with its availability increasing at top ports and can help reduce greenhouse gas emissions if produced from green sources.

Case Studies

The world's first methanol fuelled ship was constructed by Westfal-Larsen. The ship has a 10,320 kW MAN designed Hyundai– B&W 6G50ME-9.3 ME-LGI dual-fuel, two-stroke engine that can operate on methanol, HFO and MGO/MDO. Lindanger can travel at a speed of 15.8 knots [53].

In 2016 the world's first 7 methanol fueled tankers were launched by Waterfront Shipping. There were another 4 completed in 2019 and 8 on order for delivery between 2021-23 [54].

In May 2020 Maersk, DSV Panalpina, DFDS, SAS and Ørsted formed a partnership to develop an industrial-scale sustainable fuels production facility in Copenhagen. When fully-scaled up by 2030, the project will deliver 250,000 tonnes of sustainable fuel, including renewable methanol for Maersk fleet.

Damen Shipyards in The Netherlands has developed a new concept OSV to operate on methanol which allows reduction of well-to-propeller CO_2 emissions by approximately 70%.

Methanol can also be utilised in fuel cells. Methanol can be used in PEM fuel cells that operate with an upstream reformer. Methanol fuel cells produce hydrogen, through steam reforming, which reacts with oxygen in the fuel cell to produce the electricity required for the propulsion as well as the on-board power supply. Freudenberg Sealing Technologies has developed such a fuel cell operated with methanol in a container design with a view to its implementation in shipping [55].

The Viking Line ferry *Mariella* has a 90 kW system comprising of methanol-fuelled PEM fuel cells. The fuels cells were developed by Fischer Eco Solutions and SerEnergy. They feature internal methanol reformers for hydrogen production which then reacts with oxygen to produce electricity required for propulsion of the vessel.

Started in February 2019, The Green Maritime Methanol project aimed to investigate the feasibility of methanol as a sustainable alternative transport fuel in the maritime sector with collaboration between major ship builders, ship owners, engine manufacturers and ports. Infrastructure and supply chain challenges/opportunities for methanol were to be addressed by the participation of The Netherlands' two largest ports; Rotterdam and Amsterdam, as well as methanol suppliers BioMCN and Helm Proman. The project concluded that a significant part of the short sea market would be suitable for methanol. The report estimated that methanol bunker demand could grow to 5 million m^3 by 2030 in the Amsterdam-Rotterdam-Antwerp region alone [56].

Fastwater is a consortium formed in 2020 to demonstrate the feasibility of retrofit and newbuild vessels to operate on methanol as a pathway to fossil-free shipping. The Fastwater Project has received funding from the Europeans' Horizon 2020 research and innovation programme.

5.4.5 Molten Salt ReactorsA

Molten Salt Reactors (MSR) have been proposed as an energy source for decarbonising shipping. In an MSR, nuclear fuel is dissolved in a mixture of molten fluoride salts which act as a coolant. The molten salts (usually lithium-beryllium fluoride and lithium fluoride) remain in the liquid state from around 500 °C to 1,400 °C which is different to conventional pressurised water reactor (PWR) operating conditions of around 300 °C and 150 bar. The increased temperature allows for smaller designs. Increased temperature also allows operation at lower pressures. It is suggested that this design offers advantages, such as simplicity and safety over traditional solid fuel pressurised water reactors. [57] [58].

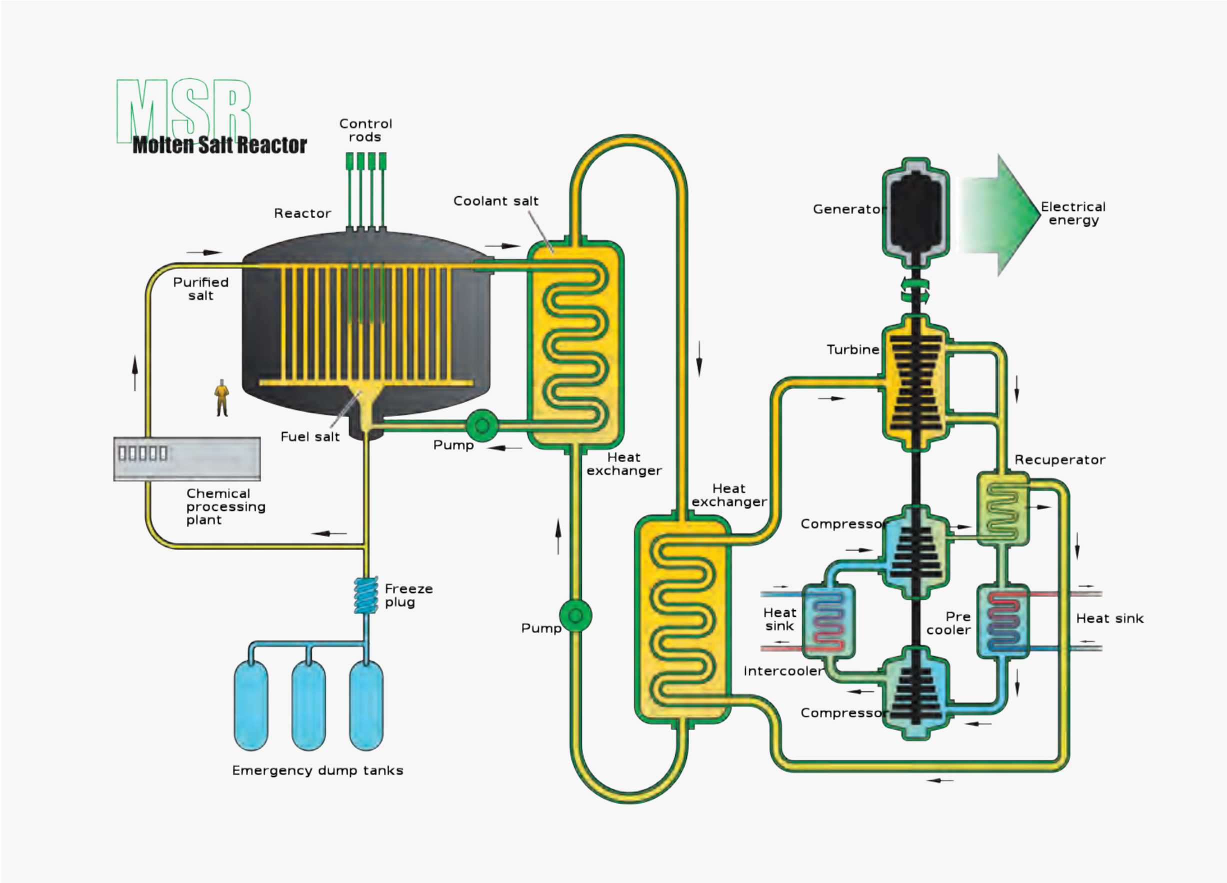


Figure 5.20: Molten salt reactor.

This technology has started to be adapted for commercial vessels. A closed system MSR has the potential to last the lifetime of the vessel without fuelling and zero emissions. Although it is envisaged that commercial MSR vessels could be operational by the mid 2020s [59], substantial regulatory work would be required before deployment and there are currently no public plans for vessels in the OSW O&M sector.

5.4.6 Batteries for Electrical Storage OnboardA

The main source of high performance, long lasting batteries are lithium-ion batteries [60]. The lithium refers to the material of the positive cathode within the battery, but they can be further split out into the following four most common types.

Table 5-12: Lithium-based batteries.

Type of Battery	Energy Density	Life Cycle	Charging Rates	Comments
Lithium Cobalt Oxide ($LiCoO_2$)	High	Low	Low	Commonly found in older consumer electronics.
Lithium Iron Phosphate ($LiFePO_4$)	Low	Medium	Medium	-
Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)	Medium	High	High	Preferred for electrical vehicles and vessels.
Lithium Manganese Oxide ($LiMn2O_4$)	Lower than ($LiCoO_2$)	Lower than ($LiCoO_2$)	High	Low energy density and charging rates make it unattractive.

The integration of battery power into vessels occurs from pure battery powered propulsion, to a sliding scale of hybrid solutions with varying reliance on engines and batteries to power auxiliary ships systems and propulsion.

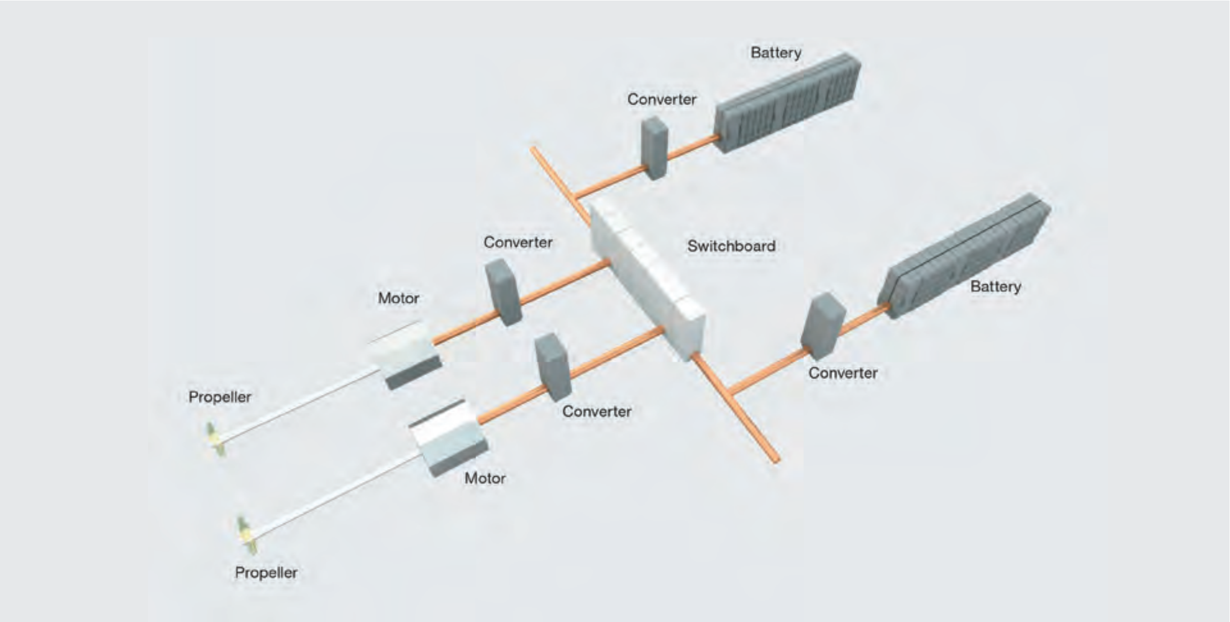


Figure 5.21: Pure battery propulsion [60].

Figure 5.21 depicts a pure electric driven vessel where the batteries are connected to electrical motors and this drives the propellers, batteries are usually charged at dock side and can be subsidised by an engine for longer voyages or should there be an issue with the battery system. Currently, due to the power output of batteries, pure battery powered vessels are not common as they can't cover distances of traditional vessels.

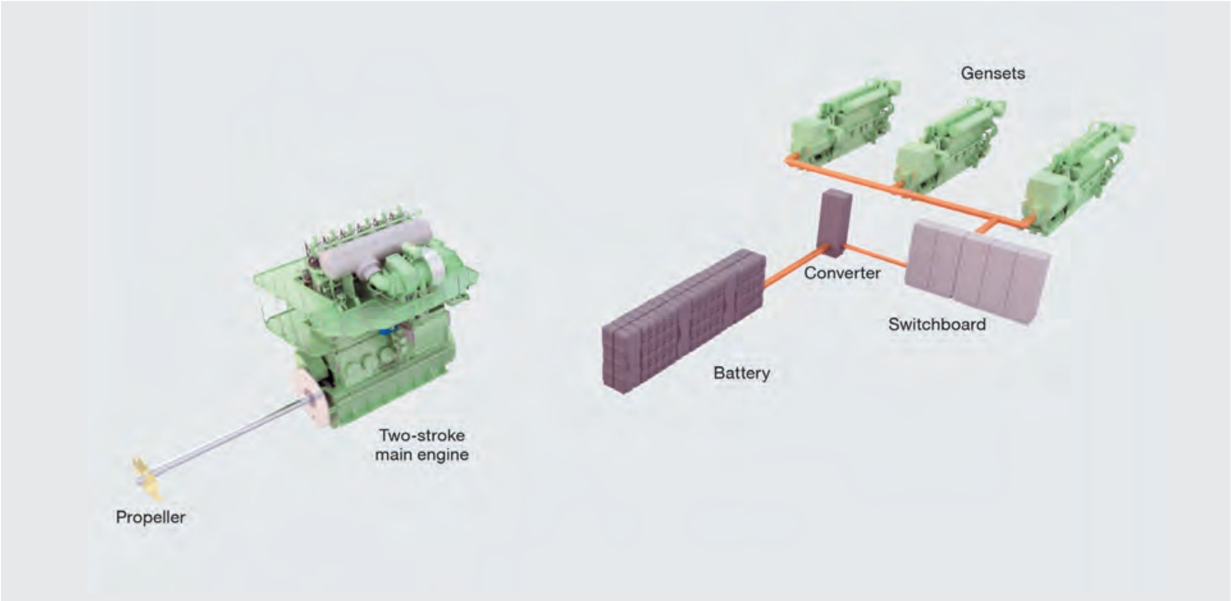


Figure 5.22: Semi hybrid - 2 stroke engine with hybrid electric grid [60].

In Figure 5.22 a schematic is shown with a standalone two stroke engine for propulsion and gensets linked up to the electrical grid of the vessel. In this case a battery bank is included within the system that can help with peak load shaving for marine systems with fluctuating loads. Improving performance and stability whilst drawing down from green electricity.

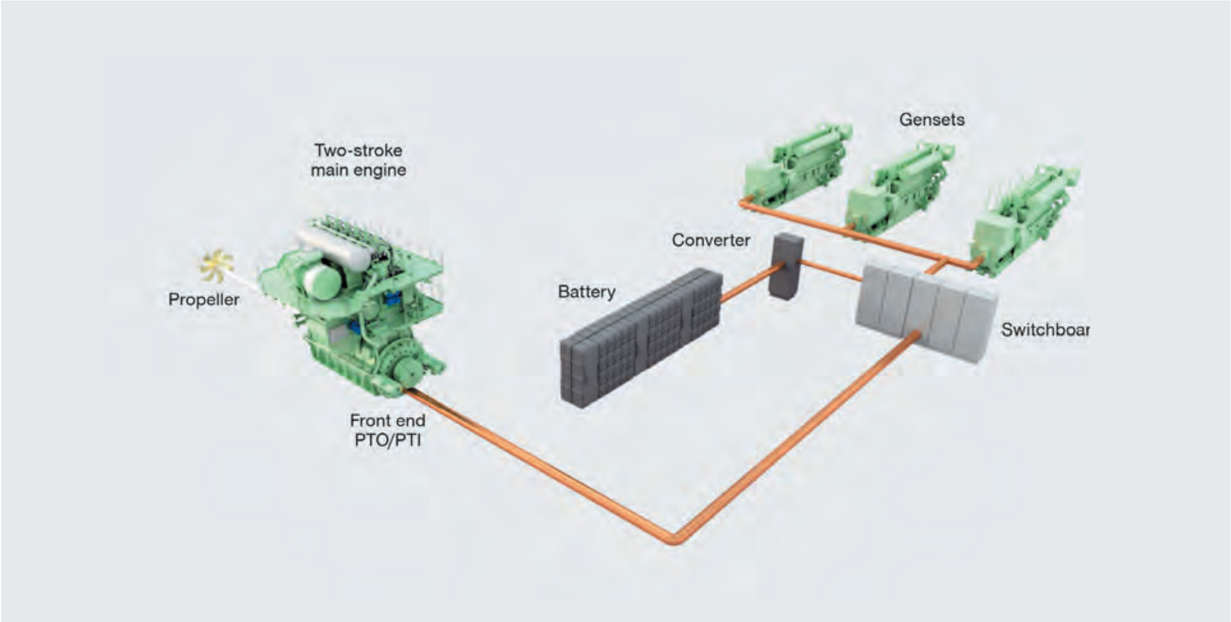


Figure 5.23: Full hybrid - 2 stroke engine with front end power take off [60].

Figure 5.23 depicts a modified design to Figure 5.22 where the battery and gensets are connected to a front-end power take off, which allows for them to support the engine in propelling the vessel.

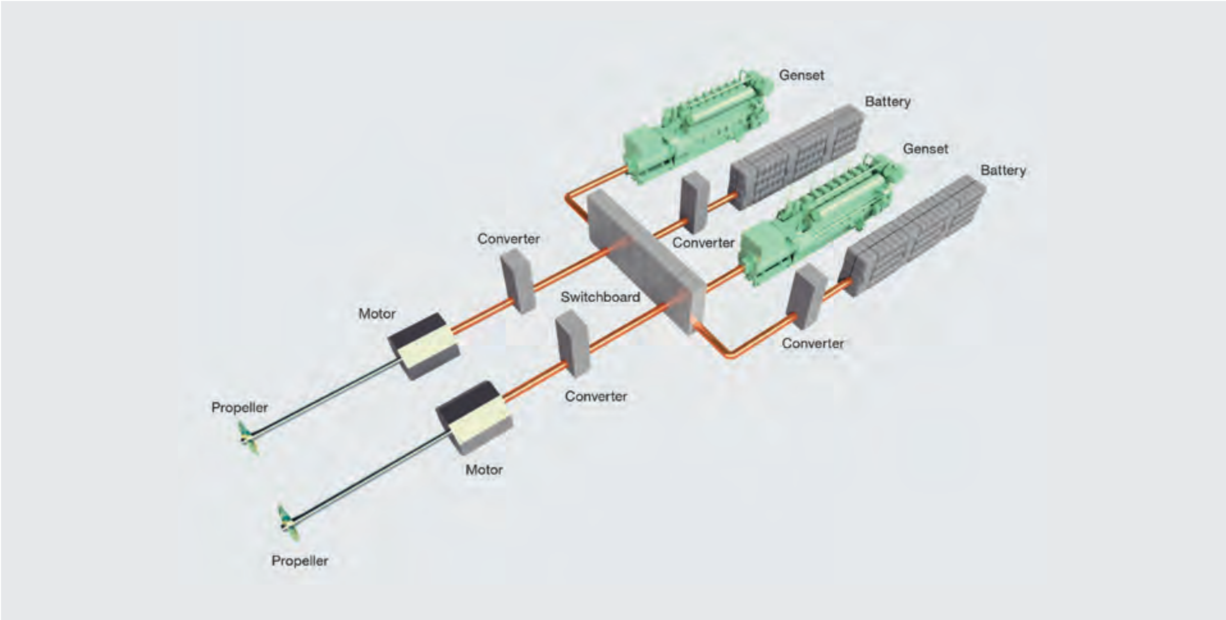


Figure 5.24: Full-hybrid diesel-electric propulsion with batteries in a hybrid system [60].

A full hybrid system is shown in Figure 5.24 where batteries support the gensets in electric generation to the switchboard to power motors for propulsion as well as vessel systems that run off the electric grid.

Provided in Table 5-13 is a list of electric vessels with their battery capacity and area of operation.

Table 5-13: Examples of electric vessels [61].

Name of Vessel	Power Output	Area of Operation	Comments
Stena Jutlandica	50,000 kWh	Gothenburg, Sweden to Frederikshavn, Denmark	Will travel the distance between cities on batteries only.
AIDAperla	10,000 kWh	Cruise ship	Retrofitted batteries work in conjunction with diesel engines.
Ellen	4,300 kWh	Danish Baltic Sea	100% electric ferry.
Project e5	4,000 kWh	Tokyo Bay	Two electric propulsion tankers used to fuel supply vessels in the bay of Tokyo.
Guangzhou Tanker	2,400 kWh	Pearl River Guangdong, China	70 m long, 14 m wide tanker with more than 1,000 lithium ion batteries giving a range of 80 km.

5.4.7 Methods to Improve Efficiency and EmissionsA

5.4.7.1 Air LubricantsA

Air lubrication is a way to reduce drag between the ship's hull and the seawater by injecting air bubbles from the bottom of a ship's hull, creating a layer of air bubbles along the bottom of the hull.

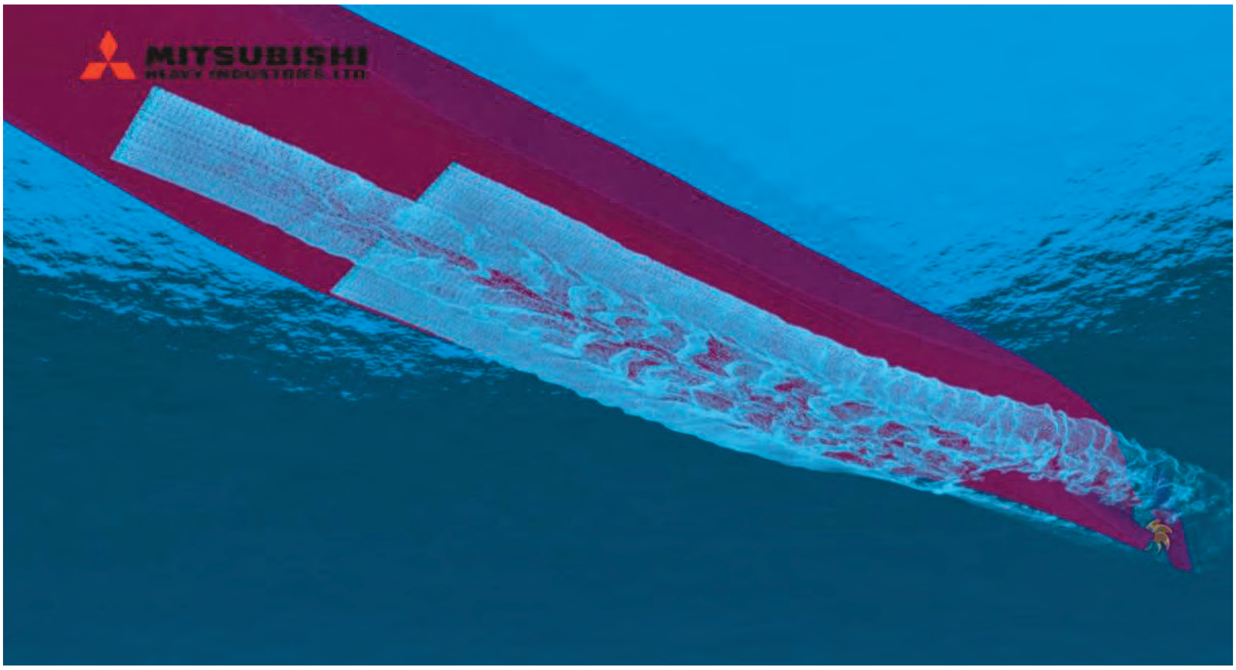


Figure 5.25: Air lubrication on vessel hull [62]. Image courtesy of Mitsubishi Shipbuilding Co. Ltd.

Air lubrication is expected to lead to a 10-15% CO_2 emission reduction, as well as a saving in fuel costs to the vessel operator.

5.4.7.2 SO_x Scrubber SystemsA

Reductions in SO_x can be achieved by cleaning exhaust gases using a scrubber. Wärtsilä have developed open, closed and hybrid scrubber systems that use the same concept of removing SO_x particles from exhaust gasses. Exhaust gasses enter the scrubber, they are sprayed with water which reacts with the SO_x to form sulphuric acid. Open systems use salt water to neutralise the acid, whereas in a closed system they use caustic soda. Hybrid systems use the open system while the vessel is in transit and the closed system when the vessel is in harbour or manoeuvring [63].

5.4.7.3 Selective Catalytic Reduction and Exhaust Gas RecirculationA

Selective Catalyst Reduction (SCR) is a process for reducing NO_x emissions produced after the combustion process by injecting a catalyst into the exhaust stream of a diesel engine as shown in Figure 5.26. The injectant is usually Diesel Exhaust Fluid (DEF) which reacts with the exhaust gases and converts the NO_x into nitrogen, carbon dioxide and water, significantly reducing the amount of harmful emissions released to the atmosphere. This also forms part of the International Maritime Organization's (IMO) tier 3 regulations that introduced new fuel quality requirements coming into effect from July 2010 for all new engines. Tier 1 requirements apply for engines pre 2000 [64].

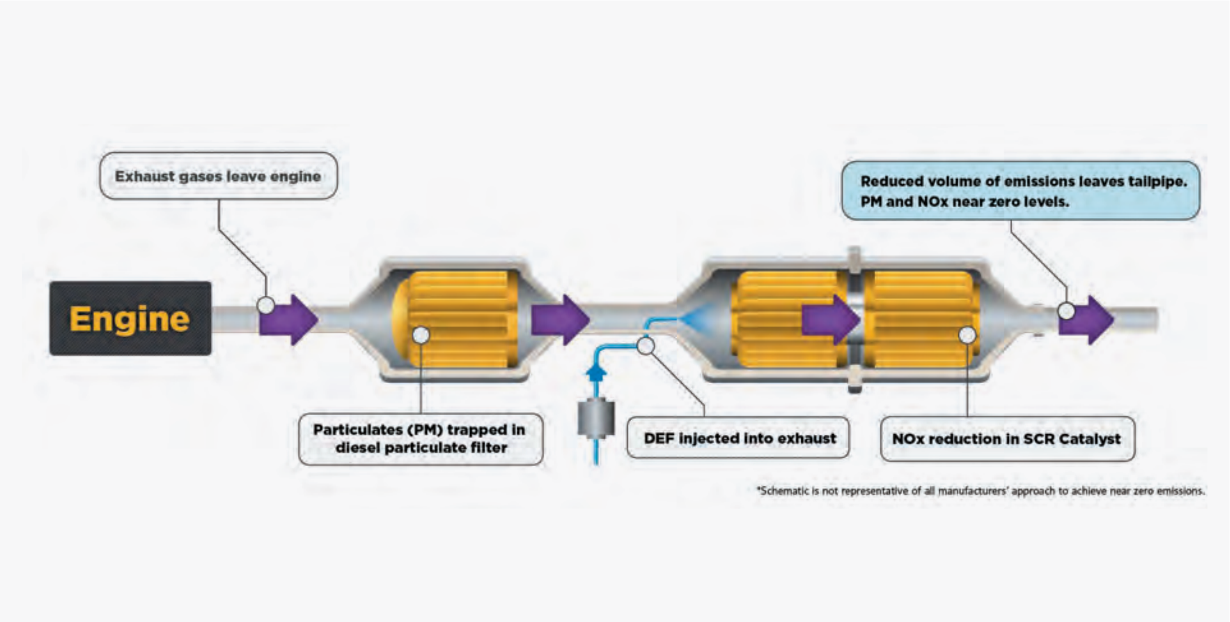


Figure 5.26: Selective catalytic reduction. Image courtesy www.dieselforum.org.

In the Exhaust Gas Recirculation (EGR) process a portion of the exhaust gases are first cooled and then recirculated back, with fresh air into the cylinder. As the air mixture has been cooled and has less oxygen within the mixture, it combusts at a lower temperature, reducing SO_x and NO_x particulates by up to 70% as these are formed at high temperatures [65].

5.4.7.4 Wind Propulsion

There are a few modern wind propulsion designs, but these do not lend themselves to SOV and CTV designs and are more aimed at larger ocean container vessels. The examples are shown in Figure 5.27 and Figure 5.28. One technology uses sails or a kite to pull the vessel reducing load on the engines and improving fuel efficiency, and the second use the Magnus effect produced by spinning cylinder pillars to drive the vessel forward [66].

Figure 5.27: Kite providing vessel propolsion assisstance. Image courtesy of SkySails Group GmbH [66].

Figure 5.28: Flettner rotors by Wilsca/CC 4.0 [66].

5.5 Portside Infrastructure

As the drive towards a net zero society builds momentum, greater investment and collaboration between government and the private sectors will reduce the cost of lower/zero emission fuels. Port infrastructure is key to allowing and encouraging the collaboration between various parties in their efforts to decarbonise CTV and SOV activities in the North Sea.

As of December 2020, there were 126 CTVs and 15 SOVs providing crew transfer and support to 59 wind farms for O&M activities in the North Sea. This fleet is comprised of 36 different vessel owners. There is a great scope for port owners, vessel owners and operators to collaborate towards a zero emissions future.

There are significant challenges decarbonising vessels, not least the portside infrastructure that will be required. Challenges include: large-scale capital investments in plant, bulk storage and distribution, safety and security considerations and early development stage of emerging, clean technologies.

There are different production, delivery and storage requirements depending on the type of alternative powering operation being considered. The decision to co-locate the production, storage and end use of a fuel will be dependent on the technology, or a range of technologies, used. Centralised and decentralised production infrastructure will bring different challenges.

This section on port infrastructure will briefly address the viability and challenges that accompany the use of the following alternative powering technologies: Hydrogen, LNG, methanol, ammonia, fuel cells and batteries. For each fuel type, attention will be given to the fuel production, supply and storage. Shore powering will also be addressed.

5.5.1 Fuel BunkeringA

Fuel for ships is stored onboard in tanks called bunker tanks. Bunkering is the operation of refuelling (or filling up the bunker tanks) on a vessel, from an outside source. There are three principal modes by which liquid or gaseous fuels are bunkered (pumped through a hose) to a ship:

- Bunkering from port fuel storage tanks
- Bunkering from a road tanker
- Bunkering from another vessel (e.g. bunker barge)

The fuel supply method developed by a port will depend on the distance from the source of the fuel, and the cost and ease of transport, including storage volume requirements and specific H&S considerations.

Currently, most CTVs in operation run on MGO (marine gas oil), and SOVs run on IFO (intermediate fuel oil). IFO has a higher proportion of heavy fuel oil. Bunkering operations are well established and are controlled by national regulations.

The world global bunker demand is about 250-300 million metric tonnes HFO/ MGO. Europe is responsible for one fifth of this volume [56].

Bunkering operations will depend on the specific fuel type being bunkered. An outline of necessary processes for each fuel type is detailed in Sections 5.5.1 to 5.5.5.

Ship to ship bunkering or bunkering from a road tanker would minimise port investments in terms of equipment, vessels, and space required for storing fuels at the port. However, this brings up the issue of supply security. There is a case to be made for some of the alternative fuels to be produced at a port thus assuring supply security. Cost and space implications would need to be considered.

5.5.1.1 Fuel Storage & Volumetric Energy DensitiesA

Consideration of spatial constraints is often an issue for ports. Any area taken up by fuel storage (and production) is land that is potentially revenue generating. Gaseous hydrogen would need to be stored at pressure to reduce the storage tanks footprint in a port and to contain the required amount of hydrogen given its low volumetric energy density.

Table 5-14 shows the volumetric energy densities of various alternative fuels, and the required additional storage volume compared with diesel. With the requirement for high pressure or low temperature (cryogenic) storage, the complexity and therefore cost of storage will increase.

Table 5-14: Comparison of volumetric energy density of alternative fuels.

Fuel	Storage Conditions (°C, bar)	Volumetric energy density (kWh/l)	Storage volume required compared to diesel	Storage vessel and equipment complexity/ cost
Diesel	Ambient	10	1	Low
Gasoline	Ambient	9.2	1.1	Low
Hydrogen Gas	Ambient	0.003	3,333	Low
Hydrogen Gas	500 bar	1.1	9.1	Moderate
Hydrogen Gas	700 bar	1.4	7.1	High
Hydrogen Liquid	-253 °C	2.3	4.3	High
LNG	-165 °C	5.8	1.8	High
Methanol	Ambient	5.4	1.9	Low
Ammonia Liquid	Ambient	3	3.3	Low
Ammonia Liquid	-33 °C	3.6	2.7	Moderate

5.5.2 Hydrogen BunkeringA

A pipeline network could be the most cost-effective option for largescale use of hydrogen as an energy source. The initial investment to establish pipelines would be high, and demand would need to also be high to justify the expenditure.

Worldwide there are over 4,500 km of pipeline. Existing natural gas pipelines could be used to transport hydrogen. Hydrogen could be blended with the natural gas, and then extracted using purification and separation technologies at, or close to, the point of use. This delivery method would mean lower expenditure for the initial supply of hydrogen to market, with dedicated hydrogen networks being established once the demand was high enough to justify the expense. It would be possible to introduce up to 15 vol% hydrogen to natural gas pipelines without substantial negative impact on the pipeline infrastructure or the end user [67].

5.5.2.1 Gaseous Hydrogen

Hydrogen's low density has an impact on its transport. Under standard conditions hydrogen has a density of 0.09 kg/m3. Compressed to 200 bar the density increases to 15.6 kg/m3 and compressed to 500 bar the density becomes 33 kg/m3

Compressed gaseous hydrogen is generally transported by truck in compressed gas cylinders, by pipeline, or it can be blended with natural gas in the existing natural gas pipeline infrastructure. Road transport in compressed gas containers is generally used for small to medium quantities of gaseous hydrogen, up to approx. 500 kg of hydrogen. For larger quantities tube trailers can be used to carry up to 1,100 kg of hydrogen, where a number of pressurised gas cylinders are bundled together inside a protective frame.

Compressed gaseous hydrogen can be stored in large vessels at the port and can be bunkered onto vessels by:

Portside storage tanks maintain a higher pressure than the vessels requirement, and so a cascade system is established, whereby upon the opening of valves the hydrogen would flow into the vessel under its own pressure. The drawback to this method is that large volumes of gaseous hydrogen would need to be stored, and much of the stored volume would be unusable, as once the portside storage pressure equalled the vessel pressure the hydrogen would no longer flow.

Compressors are used to provide high pressure gaseous hydrogen to vessels from a low pressure store at the port. This would be the most likely bunkering method if hydrogen is produced at the port with electrolysers.

5.5.2.2 Pressurised Systems

The risk when handling pressurised gases is not from their containment, but rather from an equipment failure scenario leading to the loss of containment e.g. a release of the gas. High pressure hydrogen storage vessels would need to be stored in a designated hazardous area with buffer zones established. The flow rate needs to be controlled during the movement of hydrogen to prevent excessive adiabatic heating. Adiabatic heating occurs when the pressure of a gas is increased by work done on it.

5.5.2.3 Liquid HydrogenA

In comparison to compressed gaseous transport, more hydrogen can be carried by a trailer in the liquid form. Liquid hydrogen trailers can be used to transport quantities up to 3,500 kg. The liquid hydrogen is loaded into insulated cryogenic tanks.

Liquid hydrogen could be transported by rail or ship. There exists already an established supply network for LNG. This technology could easily be applied to the supply of liquid hydrogen.

Hydrogen is a liquid at -253 °C. To maintain this temperature complex and expensive storage is required. There are very few hydrogen liquification plants in Europe, with limited production capacity. As demand for hydrogen increases more liquification plants and infrastructure will be required.

Storage of liquid hydrogen would require cryogenic tanks. The transfer of liquid hydrogen to a vessel would require cryogenic pumps. Alternatively, the liquid hydrogen could be converted to gaseous hydrogen. An evaporator would be needed to convert the liquid hydrogen to gaseous hydrogen, and a compressor would be required to deliver hydrogen gas at the required pressure for the vessel.

There is potential to have clean hydrogen production located within a port. Currently Less than 0.1% of global dedicated hydrogen production comes from water electrolysis. With declining costs for renewable electricity there is growing interest in electrolytic hydrogen. There are currently numerous projects related to the production of clean hydrogen. 50 GW of green hydrogen electrolysis projects have been announced in 2020 alone, along with numerous blue hydrogen with CCS projects. Many are port based, some are offshore based delivering clean hydrogen to port. A number of these are summarised in Table 5-15.

Table 5-15: A number of hydrogen production projects.

Project	Description	Location
H_2ermes	Port of Amsterdam, along with Tata Steel, and Nouryon, are investigating the establishment of a 100 MW Hydrogen plant on the Tata Steel site in Ijmuiden. The plant will have the capacity to produce up to 15,000 tonnes of green hydrogen per year.	The Netherlands – close to Port of Amsterdam
NorthH_2	Offshore wind to green hydrogen project with ambitions to have 10 GW installed electrolyser capacity by 2040 with production capacity of 1,000,000 tonnes of green hydrogen annually, with 4 GW installed by 2030.	The Netherlands-Eemshaven port location
AquaVentus	10 GW capacity offshore wind turbines in the North Sea to power green hydrogen electrolysis offshore. Production capacity of 1,000,000 tonnes of green hydrogen by 2035. Hydrogen will be transported to land by pipeline.	North Sea – between Dogger Bank and Heligoland wind farms
H_2H Saltend	Initial plans to install 600 MW capacity steam reformer with CCS to produce blue hydrogen. The project aims to produce green hydrogen by electrolysis in later stages. A large scale hydrogen network in the Humber region is envisaged.	Humber region, UK
CMB-Hydrogen fuelling station	Construction began in October 2020 on the first portside hydrogen fuelling station in Europe. The hydrogen fuelling station be able to provide green hydrogen for ships, busses, cars and trucks. CMBs Hydroville, the first hydrogen powered passenger vessel will be fuelled at this facility, as will CMBs Hydrotug, the first hydrogen fuelled tug vessel. The vessel has a hydrogen and diesel dual fuel engine.	Port of Antwerp, Belgium
Port-Jerome Hydrogen	Air Liquide and H_2V Normandy plan construction of a 200 MW installed capacity electrolyser complex capable of producing 28,000 tons of green and low carbon hydrogen annually for industry. Excess hydrogen will be injected into the local gas network. Production is due to begin in 2022.	Port Jerome, Normandy, France
Deep Purple	Offshore green hydrogen production by electrolysis powered by offshore wind. The hydrogen will be produced offshore and stored in pressurised tanks on the seabed. Hydrogen will be delivered to shore by pipeline.	Norway
HYPORT	Green hydrogen produced by electrolysis powered by offshore wind that would have been curtailed due to grid constraints. CO_2 reduction of 1,000,000 tons annually when operational by 2025.	Port of Ostend, Belgium
Gigastack	Ørsted, in partnership with electrolyser manufacturers ITM and the Phillips 66 Humber refinery, aim to produce green hydrogen by electrolysis powered from offshore wind. The hydrogen will be utilised in the refinery processes, reducing CO_2 emissions. The project plans for 100 MW installed electrolyser capacity.	Humber region, UK

5.5.3 LNG BunkeringA

Global LNG trade amounted to 359 million tonnes in 2019. As there are no LNG production facilities in the UK, currently all LNG used in the UK is imported. Transport of LNG is done by pipeline or LNG transporter vessels. The LNG pipeline infrastructures are designed to transfer liquified gas from liquification plants to storage tanks or LNG transport vessels. The network also takes LNG from tankers and storage facilities to re-gasification facilities.

Currently LNG fuel in the UK is bunkered by way of truck delivery to ports. Should the LNG demand increase sufficiently, then LNG storage tanks could be installed at ports to increase the available volume of LNG for bunkering operations. Alternatively, LNG bunker barges could be used. These could potentially be made ‘hydrogen liquid compatible’ and so could provide LNG and liquid hydrogen simultaneously.

Whilst LNG is not yet a standard bunker fuel there is substantial infrastructure already in place for bunkering LNG globally. The majority of European bunkering facilities are in Northern Europe. Table 5-16 shows LNG import, export and bunkering facilities in the North Sea region [68].

Table 5-16: LNG facilities in the North Sea region.

Location	Country	Status	Type
Port of Antwerp	Belgium	Underway	LNG bunkering facilities development projects
Brunsbüttel	Germany	Underway	LNG bunkering facilities development projects
Dunkerque	France	Operating	LNG import terminal
Gothenburg	Sweden	Underway	LNG bunkering facilities development projects
Hamburg	Germany	Underway	LNG bunkering facilities development projects
Hammerfest Port	Norway	Operating	LNG liquification Plant
Hammerfest Port	Norway	Operating	LNG bunkering facilities
Isle of Grain	UK	Operating	LNG import terminal
Kollsnes I	Norway	Operating	LNG import terminal and bunkering facilities
Kollsnes II	Norway	Operating	LNG import terminal and bunkering facilities
Lysekil	Sweden	Operating	LNG import terminal
Montoir-de-Bretagne	France	Operating	LNG import terminal
Øra Fredrikstad	Norway	Operating	LNG import terminal
Risavika	Norway	Operating	LNG export terminal
Port of Rotterdam	The Netherlands	Operating	LNG import terminal and bunkering facilities
South Hook/Dragon	UK	Operating	LNG import terminal
Snøhvit	Norway	Operating	LNG export terminal
Snurrevarden	Norway	Operating	LNG import terminal and bunkering facilities
Stockholm	Sweden	Underway	LNG bunkering facilities development projects
Port of Zeebrugge	Belgium	Underway	LNG bunkering facilities development projects
Port of Zeebrugge	Belgium	Operating	LNG import terminal

The Port of Rotterdam is collaborating with several companies to create an LNG logistic chain in Europe [69].

5.5.4 Methanol BunkeringA

Methanol is available globally and is price competitive as a fuel, it can be used with existing engine technologies. The large scale use of methanol as a marine fuel would require only minor modifications to current port bunkering infrastructure. Methanol is subject to the same bunkering guidelines and safety standards as conventional marine fuels. However due to its relatively low flashpoint of 12 °C there are additional storage and handling requirements from a safety perspective.

Methanol fuel is delivered to UK suppliers using long distance shipments. Methanol is currently available in over 100 ports worldwide. There are over 90 methanol plants with a global production capacity of 110 million tonnes. Port terminals in northern Europe have a methanol availability of 695,000 tonnes, and the Eastern Europe and Baltic region 44,000 tonnes, according to the methanol institute [71].

Methanol is the world's most widely shipped chemical commodity and is widely used feedstock in many chemical processes. Methanol is present at nearly all current centres for conventional fuel bunkering. Methanol does not have to be crygenically stored (as with LNG), and can be stored in much the same manner as conventional marine fuels [72].

Methanol bunkering can be done from trucks or by using existing bunker barges which could easily be converted to handle methanol.

In October 2020, a methanol bunkering project was launched in Ghent, Belgium. The North-C-Methanol project aims to create two large scale plants and infrastructure at the Port of Ghent. The first plant will be operating by 2024 on the Engie site and will have 65 MW of installed electrolyser capacity to produce green hydrogen powered by wind. This capacity will increase to 300 MW by 2028, and 600 MW by 2030. The green hydrogen will feed into a methanol plant to produce green methanol that will be used as a marine fuel. Excess green methanol will be utilised in other industries nearby [73]. The project will produce 44,000 tons of green methanol annually by 2030.

5.5.5 Ammonia BunkeringA

Globally there are dedicated ammonia terminals in 38 ports which export ammonia, and in 88 ports which import ammonia, including 6 ports which both export and import ammonia. Many terminals are parts of ammonia/fertiliser plants which are located at the coast of sea or river and are equipped for trans-shipment of fertilisers and ammonia. Figure 5.29 shows ammonia import and export ports in the North Sea Region [74].

Figure 5.29: Ammonia import and export ports in the North Sea.

With the current established world grid of ammonia terminals and storage, a bunkering grid could be established quickly and cost effectively by converting small gas tanker vessels to bunker barges. They would be able to utilise the existing storage facilities as base stations and from there approach the vessels requiring bunkering in the vicinity. The bunkering operation itself would be very similar to when bunkering other gaseous fuels, except the main hazard would be the fuel toxicity rather than flammability, and the procedures for ammonia bunker barges need to be developed.

Ammonia is easily compressed and stored as liquid in either atmospheric tanks or pressurised tanks depending on the tank capacity.

Ammonia is either stored in pressurised vessels at up to 20 bar and ambient temperature or in liquid form at -33 °C and atmospheric pressure. When stored in large quantity above 10,000 tons, the tank pressure is near atmospheric and refrigerated at -33 °C. Lower quantities of liquid ammonia are typically stored at ambient temperature and pressures of 10-20 bar. Storage tank walls need to be insulated to avoid material stress and potential bursting that could be caused by ammonias high coefficient of thermal expansion.

Existing practices and know-how for a safe ammonia handling are established in the marine and other industries and adaptable for ammonia as a fuel.

Japan's Itochu Corporation, along with terminal operator Vopak Terminals, have come together to study the feasibility of developing infrastructure to support the use of ammonia as marine fuel in Singapore. This includes the development of an offshore facility for ammonia vessel refuelling in the Port of Singapore [75].

Yara has announced plans to produce 500,000 tonnes of green ammonia annually at a facility in Norway, powering emission-free shipping fuels and decarbonised food solutions [76].

The Power-to-Ammonia Project is a green ammonia production facility that will be based at the Port of Esbjerg, Denmark. Due to be operational by 2026 it will be one of Europe's largest green ammonia production facilities. The project aims to produce 50,000 tonnes annually [77].

North Sea Port, a merger between Dutch Zeeland Seaports and the Port of Ghent in Belgium, announced plans for green ammonia production, which could result in an annual reduction of CO_2 emissions of 100,000 tonnes. Ørsted and Yara are working together on the project. Green hydrogen will be produced from an electrolyser facility with 100 MW capacity, powered by offshore wind. The green hydrogen will be used for green ammonia production of approximately 75,000 tons annually [78].

5.5.6 Cryogenic Liquids (Hydrogen and LNG)A

All LNG and liquid hydrogen storage system components must be suitable for cryogenic temperatures. This includes all tanks, pipes, valves, fittings etc. Welded connections should be used wherever possible to minimise the number of pipe joints, thus minimising potential for leakages. Tanks, pipes, valves, and other fittings used for handling LNG and liquid hydrogen should have a minimum design temperature of -165 °C and -255 °C for liquid hydrogen. Typically, these pipes are stainless steel. To protect the crew from exposure to extreme cold and to minimise heat influx and warming of the cryogenic liquid tank and bunker lines are typically insulated. Rigid foam or vacuum insulation techniques are used.

Natural gas in the vapour phase is readily flammable and will burn when in a 5-15% volume of air mixture. In the liquid phase natural gas is not flammable and can't ignite.

Temperature control is crucial in the storage and handling of cryogenic liquids. Should the temperature rise above -162 °C for LNG and -153 °C for liquid hydrogen, they would boil and become vapour. This process is accompanied by a decrease in density and an expansion which in a closed system (sealed vessel or pipe) will lead to an increase in pressure. This in turn could lead to equipment failure resulting in ruptured tanks and pipes, followed by an uncontrolled release to LNG and natural gas vapours.

Temperature and pressure have a great influence on the behaviour of LNG and liquid hydrogen and must be tightly controlled during bunkering operations. LNG is a cryogenic liquid at -162 oC, and hydrogen is a cryogenic liquid at -153°C. Cryogenic liquid presents a risk to any personnel and steel equipment it may come into contact with.

One novel way of bunkering cryogenic liquids would be using portable cryogenic tanks e.g. ISO tank containers as a vessels fuel tank. When empty the tanks could be replaced with pre-loaded tanks from the port delivered by rail or road. This could significantly reduce safety issues during conventional bunkering operations and shorten the procedure reducing a vessels non-productive time.

5.5.7 Ports as Energy HubsA

For many small or medium sized ports key barriers to implementing alternative fuels into their offerings for vessels is cost and demand. With there being numerous alternative fuel options and technologies for vessels to reduce emissions and decarbonise, the cost of providing support for all alternative systems would be prohibitively high. If a port decides to provide for one type of alternative fuel or technology the demand is likely to be too small from vessels to justify cost for implementation, at least when the fuel is initially implemented. The same can be said for vessel designers and operators. There is reluctance to invest in designing or retrofitting vessels for one type of alternative fuel option in case they would not be supported by the ports that they frequent.

One possible mitigation for portside expenditure would be to install infrastructure for an alternative fuel that has a demand in other sectors, not just marine vessels. There are numerous examples of ports striving to become 'energy hubs' whereby they become a point for production and distribution of an alternative fuel in order to provide for marine vessels as well as other sectors including local industry, transportation and power generation.

Details of some Ports endeavouring to become energy hubs can be found in Table 5-17.

Table 5-17: Port/hub breakdown with respective details and location.

Port/Hub	Details	Location
Freeport East Hydrogen Hub	• Felixtowe & Harwich ports • Hydrogen to be used to power port equipment, ships, trucks and trains • Nuclear, hydrogen, maritime and transport decarbonisation scheme • Will deliver 1 GW hydrogen at its peak	UK
Port of Rotterdam [79]	• Largest bio-port in the world, producing 1.2 million tonnes of biofuels annually for industry in the region including power generation and refinery processes • The port aims to become a hydrogen hub by building a public hydrogen network connected to a green hydrogen production plant. Green hydrogen will be provided to industry including the shell refinery in Pernis • Multiple hydrogen terminals will be constructed at the port for import of hydrogen from the Port of Sines	The Netherlands
Port of Sines [80]	• The Sines Green Hydrogen Project will be based at the port • By 2030 there will be 1 GW installed electrolyser capacity powered by solar PV • Production to begin in 2023 • Green hydrogen for local industry and for export • Memorandum of understanding signed with the Port of Rotterdam to establish a green hydrogen import-export supply chain	Portugal
Port of Hamburg [81]	• The Moorburg Powerstation project, close to the Port of Hamburg will be the site of green hydrogen production • Green hydrogen production due to commence in 2025 • Green hydrogen will be supplied to the port for use and export	Germany
Port Jerome [82]	• Situated in Normandy, France • 200 MW installed electrolyser facility powered by wind and solar • Green Hydrogen utilised for local industry including refining • Green hydrogen transported to the Paris region to hydrogen stations for charging a fleet of zero emissions taxis	France

5.5.8 BatteriesA

The use of battery powered road vehicles is well advanced, in part due to advances made in lithium battery technology, allowing lighter weight batteries, that can hold a charge for longer and can withstand charge/discharge cycles better than previously developed lead-acid batteries. A typical lithium-ion battery can store 150 watt-hours of electricity in 1 kg of battery and has a power density of 50-2,000 W/kg. Efficiency of lithium ion batteries range between 85-99%

Batteries for electric vehicles are designed for high kWh capacity. They are characterised by their relatively high power to weight ratio, their specific energy and their energy density. Most current battery technologies have a low specific energy density when compared with liquid fuels. As a result, electric vessels have a limited maximum range between charges. For near shore wind farms (<40 km from shore) the use of hybrid electric vessels is growing. The potential for offshore charging capabilities at wind farms would mean, even with range limitations of current battery technology, they could be employed for CTV and operations farther offshore.

Batteries used in electrical vehicles must be periodically recharged. Good battery lifespan is usually achieved at charging rates not exceeding half the capacity of the battery per hour. A normal household in European countries, with 230V electricity, can deliver 7-14 kilowatts. The higher the voltage available, the higher the kilowatts that can be delivered.

The family of lithium batteries is vast. Some types offer high energy density or high power density. Some others, like Lithium Titanium Oxide (LTO), have superior thermal stability for fast charging and discharging but offer lower capacity typically 50-70 Wh/kg.

Because of the massive variety in types of battery, and thus variety in voltage and frequency requirements, it is not possible to provide a standard charging solution and equipment can be complex and costly. Charging is generally done using a direct electrical connection known as a conductive coupling.

Finding the economic balance of range vs performance, battery capacity vs weight and battery type vs cost is the challenge for battery implementation in maritime vessels.

Fully electric or electric hybrid marine vessels are seen as a real contender in the market because of their ability to reduce CO_2, SO_x, NO_x and particulate emissions. By using renewable electricity to charge batteries and not taking into account potential emissions during manufacture, emissions can be virtually eliminated with a fully electric vessel.

There are already over 100 manufacturers of electric boats and ships worldwide, and many examples of operational vessels, including:

- The Norwegian ferry MF Ampere undertakes 56 journeys of 5.6 km per day and is powered by a 1.04 MWh lithium-ion battery, which is recharged by two 410 kWh shore charging stations located at each end of its journey [83].
- Caledonian Ferries has three hybrid vessels, each having two banks of 800 kWh of

batteries. Planet Solar has 8.5 tons of Lithium-ion batteries in its two hulls with solar cells to recharge them.

- ZEMSHIP has a 2.5 kWh lithium battery working in a hydrogen fuel cell hybrid system.
- Yara Birkland was the first all-electric container ship, delivered in 2018.

The major drawbacks associated with electric vessels utilising battery power to date are:

- Batteries have low energy densities compared with liquid fuels and thus require larger batteries to fulfil speed and range demands.
- High capital expenditure of the batteries.
- The need for recharging infrastructure at ports.

There is significant potential for electrified vessels being utilised for near shore wind farms with the appropriate shore-powering facilities in place. Vessels could have greater ranges with the utilisations of shore-power combined with the use of offshore charging technologies, such as those discussed in Section 5.6.

5.5.9 Modular BatteriesA

With battery technology advancement being rapid, electrification of vessels is increasingly being seen as a viable technology for marine vessels in the drive to reduce emissions and achieve net zero. There is however some reluctance for vessel owners to invest in battery technology that could be very quickly superseded by new battery technologies. One novel way that this issue can be addressed is by investing in vessels that are equipped with modular, containerised battery systems. A modular, standardised battery room housed within a container can be fitted to a vessel to provide a complete energy storage system that can offer flexibility to a vessel owner. If a vessel requires additional electrical capacity additional modules can be added. The containerised battery system can be exchanged as new technology becomes available. The containerised battery would be suitable for new vessel designs and retrofit vessels.

By using a containerised battery solution, a vessel is able to change out, or adapt a system as required. There is also the potential for these systems to be utilised to enable a vessel to switch out a depleted battery and replace with a fully charged battery in port. This could significantly reduce the time a vessel needs to spend in port charging batteries using shore power. A battery station could be set up at the port, where containerised batteries are charged, using either renewables or connected to the grid, and when a vessel comes into port it can change out its depleted containerised system with a charged one. A number of companies are working on implementing this technology.

Case study

Corvus Energy

Corvus Energy has a system called the Corvus BOB (battery onboard) that it is suitable for a wide range of vessels [84]. The system can be seen in Figure 5.30.

Figure 5.30: Corvus BOB container. Image courtesy of Corvus Energy.

In June 2020 the Port of Rotterdam, in partnership with Engie, launched ZES (Zero Emissions Services). The project aims to provide replaceable battery containers (ZESPacks) to vessels to allow for electrical propulsion of inland container vessels. The vessels instead of having to charge batteries in port, can switch out their depleted batteries with a new battery container as needed. The battery container charging stations will be located in the port and will be powered by wind turbines. The battery containers would have a range of up to 100 km before needing to be replaced. The first customer has signed up to the scheme. Heineken beer company will use the ZESPacks on their vessels to transport beer from its brewery in Zoeterwoude to Moerdijk [85].

Sterling PlanB Energy Solutions are working as part of a consortium in The Port of Singapore to install this technology. The Port is the second largest in the world, with up to 1,000 vessels at the facility at any one time. A modular battery interchange system will enable electric vessels to be able to access charged batteries whenever in port, and the depleted batteries can be charged using renewables or charged at a time when there is the least demand on the local grid. The modular battery interchange system (PWRSWÄP) is able to switch a vessels battery system within 2 minutes which is considerably more time efficient compared to shore powered charging.

5.5.10 Shore Power

Shore Power involves a ship connecting to shore side electricity infrastructure to charge while at berth. This allows main and auxiliary engines to be turned off, significantly reducing vessels' emissions whilst at berth. It is a proven technology that could be implemented, however the cost implications have been a barrier to its implementation to-date.

Advances are being made in shore power technologies and many countries are taking actions to commercialise it. The German government recently invested over £100 million into shore-power infrastructure. China has begun investing in a major shore-power expansion programme. Increasingly, new build ships are coming out with shore powering technology fitted as a standard.

Large vessels including cruise liners, ferries, and container ships appear to be a major driving force for ports installing shore powering infrastructure. The port of Kiel, in Germany, opened its onshore power supply plant in December 2020, capable of supplying Stenaline ferries with eco power. Two vessels are able to dock at any one time and connect to charging facilities at the port. By 2024 the port of Kiel want to be able to supply green shore power for up to 60% of the cumulative electrical energy demands of vessels berthing in Kiel [86].

The ports of Stockholm, Copenhagen, Aarhus and Helsinki have a joint initiative to reduce emissions in their portside areas by investing in shore powering facilities [87]. The port of Stockholm has begun work to install HV onshore power connections to two of its central quays. Work is due to be completed by 2023/24.

The port of Victoria, BC, is investing over $20 million (USD) on its shore power project. There will be two berths providing power to 75% of cruise ships berthing in Victoria. By 2040, 95% of cruise vessels will be shore power compatible at the port [88].

Ports in California have invested heavily in shore power infrastructure. Regulations that came into force in 2014 pertaining to clean air requirements have been the key driver for shore powering investments. As of 2014 at least 50 percent of fleet vessel calls must shut down their auxiliary engines and run their vital onboard systems by plugging into shore-side power. By 2020 the requirement was 80% [89]. The port of Los Angeles was the first port in the world to use shore power technology for in-service container vessels. The port has more berths equipped to provide shore power than any other port in the world. Vessels can utilise shore power facilities at 8 container terminals and at the port's world cruise centre. Over $180 million has been invested into shore power infrastructure at the port.

If a port were to invest in necessary equipment to provide shore powering for vessels the pay back for such an expenditure is likely to be slow due to the potentially slow rollout of electrical vessel technology, giving rise to low demand for shore powering facilities. The cost of electricity from shore powering facilities at ports would also likely be more expensive, without subsidies, than the cost of a vessel charging their batteries using their own auxiliary diesel engines.

The British Society of Maritime Industries held a seminar in early 2021 to discuss the viability of shore power. The findings suggested that if ships invested in the technology for shore powering they could expect a payback in 3 years, with payback for ports being slightly longer at 4 years [90]. At the seminar the fleet director of Royal Caribbean International Cruises estimates that it is 10 times more expensive to retrofit a ship for shore power than it would be to include the technology in a new build ship.

There are major barriers to the implementation of shore power. Projects can be complex and expensive. Currently, there are only two major shore power projects in the UK (excluding Royal Navy projects). One in Orkney, to charge the MV Hamnavoe NorthLink ferry and one in Southampton due to open for shore-powering cruise liners in 2021.

Installing shore-power capability at a port requires high capital investment. Actual costs depend on various factors, including:

- Demand and load profiles from vessels
- Charging terminal requirements
- Outside port grid reinforcement requirements
- Substation requirements
- Cabling (HV cables needed)
- Switch-gear
- Frequency conversion equipment
- Available grid capacity

The main components of shore-power projects are outlined in Table 5-18.

Table 5-18: Main components of shore power projects [91].

Category	Components	Cost
Grid to port	Grid upgrades required including substations.	Potentially high. In the millions for remote/ old ports with no established infrastructure.
Port	Transferring power from the grid to mooring vessel.	Potentially high. Dependent on the number of berths.
Port to vessel	Compatibility issues. Frequency convertor may be required if a vessel runs at frequencies other than grid frequency (50Hz).	Low to moderate. For a 2 MW connection £0.3-0.3 m. Higher with frequency conversion.

From a ship owner/operator standpoint, the introduction of electric or electric hybrid vessels presents its own challenges including:

- Availability of shore-power at all ports.
- Short times at berth. Charging needs to be rapid enough to not impede a vessel's normal operations.

- Potential high cost of electricity from shore-powering. Many smaller hybrid vessels would be reluctant to pay for shore-powering when it would be more expensive than generating their own electricity from diesel engines.
- Lack of standardisation. Many ships do not have the same voltage/frequency requirements.
- Energy density and impact on endurance. Currently most coastal ships use marine diesel oil which typically has an energy density of 42,190 kJ/kg and volumetric density of 39,970 kJ/l and costs 42.3 $/MWh (MGO price 500 $/t) whereas the best available commercial battery has an energy density of 1,224 kJ/kg and a volumetric density of 2,434 kJ/l and costs 73.2 $/MWh (wholesale price of electricity 0.0732 $/kWh) [92].

5.5.11 Opportunities and BarriersA

Port infrastructure considerations are numerous and complex. With the myriad vessel operation options, each one presenting its own combination of supply, storage and bunkering requirements. The table below attempts to capture potential opportunities and barriers to the application of each alternative fuel/powering option. The likelihood that dual systems, and or a combination of alternative fuels will be required by different vessel owner/operators, only adds complexity to port owners/operators when attempting to upgrade port facilities to support efforts to 2050 net zero.

The comparison of alternative fuel opportunities and barriers is outlined in Table 5-19.

Table 5-19: Comparison of alternative fuel opportunities and barriers.

Fuel	Advantages	Disadvantages
Hydrogen	• Can be used in a dual fuel system with minor engine modifications • Numerous zero carbon production technologies, including electrolysis where oxygen is the only by-product • Potential to ‘piggy back’ off LNG supply and transport infrastructure already in place • Production cost is expected to plummet during the next 10 years	• Lack of supply infrastructure • Cryogenic/pressurised storage is expensive • Production costs can be high depending on method (electrolysis for green hydrogen) • Scalability of production dependent on demand
LNG	• Established supply chain • Can be used in a dual fuel system with minor engine modifications	• Transition fuel. Still a CO_2 emitter
Methanol	• Relatively simple engine modifications to run on methanol • Established supply chain	• Transition fuel if produced from fossil sources. CO_2 emitted during combustion
Ammonia	• Established supply chain • Better volumetric energy density	• Handling and storage issues due to toxicity
Batteries	• Opportunity for shore power projects to be included with greater port projects, e.g. electrolyser plant using grid power • Potential to power offshore charging infrastructure with electricity produced at a nearby wind farm	• Low energy density • Limited range • High cost of batteries • Lack of charging infrastructure • Battery lifespan • Battery disposal issues

5.6 Offshore Charging Infrastructure

As an alternative to portside charging, offshore charging allows vessels to charge/fuel up offshore, therefore extending their operational range and reducing emissions. The technology would be applicable to both fully decarbonised and hybrid vessels, as well as make a number of developing zero carbon fuels and technologies (e.g. hydrogen and batteries) more competitive with conventional fuels.

It is highly likely that offshore charging of CTVs and SOVs will be needed to meet the requirements of wind farm owners and operators in order to decarbonise the operation and maintenance activities of the sector. Within this section a number of developing technologies, mainly electric, are reviewed.

5.6.1 Mara BuoyA

The Mara Buoy system is a 4-point mooring and dynamic cable buoy system designed to charge battery powered CTVs in the field. The technology developer envisages 2 – 3 buoys strategically placed within a wind farm and each supplied with power from a wind turbine. A CTV will connect to the buoy via a dedicated boat hook system. Once connected, a telemetry signal will be set to the wind turbine which will electrify the buoy and start charging the CTV. The buoy system is currently being designed to a 2 m significant wave height to match standard maximum CTV operating conditions.

There is a technology gap in offshore charging of vessels. These require electrical connectors but no standard specification is available. Depending on the power requirements, significant modifications, including large components, to wind turbine and/or vessel would be required. In the case of the latter, this would have a knock-on effect on the available space and payload capacity of the CTV.

There is also the challenge of designing an electrical charging system that can recharge CTV batteries in 1 – 1.5 hours, which is the expected downtime of a vessel in the field while maintenance activities are underway.

Whilst initially aimed at the CTVs in offshore wind, the technology could be developed and utilised by fishing and leisure vessels with the buoy being powered from shore (240 V AC) and located in geographically protected areas such as estuaries and sea lochs.

At the time of the report being written (Q1 2021), the design prototype of Mara buoy was priced and fabricated using UK supply chain with the aim of having a working prototype in the water for April 2021, with release of a commercially available product is planned for early 2022.

On top of the technology barriers there also needs to be a requirement for CTV charging offshore, a chicken and egg scenario where the sector is not seeing a large-scale push towards electrification currently. This has been considered in the design as the buoy system could be interchangeable and used to recharge hydrogen powered vessels (fuel cells or combustion) if additional renewable electricity was used to generate hydrogen offshore.

5.6.2 Maersk Power Buoy

Maersk Supply Services have partnered with Ørsted to develop a prototype buoy that will act as a mooring point and charging station for vessels, but predominately aimed at SOVs. The design of the buoy is being handled by Maersk while the integration of the buoy in an offshore wind farm will be carried out by Ørsted and is planned for 2021 [93].

The buoy will be designed for a single vessel with enough capacity to charge smaller batteries or hybrid-electrical vessels, as well as to supply power to larger vessels, enabling them to turn off their engines when laying idle. Maersk has plans for the buoy to be used for vessels across the maritime sector.

The demonstration stage of this project has received a grant of DKK 22 million (GBP 2.57 million) from the European Development Fund and Ørsted intends to make the intellectual property of the design publicly available to maximise uptake of the technology [93].

Figure 5.31: Visualisation of Maersk buoy. Courtesy of Maersksupplyservice.com.

Both, the Mara and Maersk buoy, look to tackle a number of the problems highlighted within the O&M activities of wind farms by lowering vessel emissions, offering a safe mooring point and reducing engine noise.

5.6.3 MJR Offshore Electrical Charging SystemA

MJR Power and Automation, together with a number of industrial partners, have developed design concepts for an offshore charging system. The system allows CTVs and SOVs to dock and recharge from batteries which draw down excess power from an offshore wind farm's electrical infrastructure. This leads to greater investment confidence in battery powered vessels, as well as increases their operating windows offshore, which subsequently reduces O&M costs.

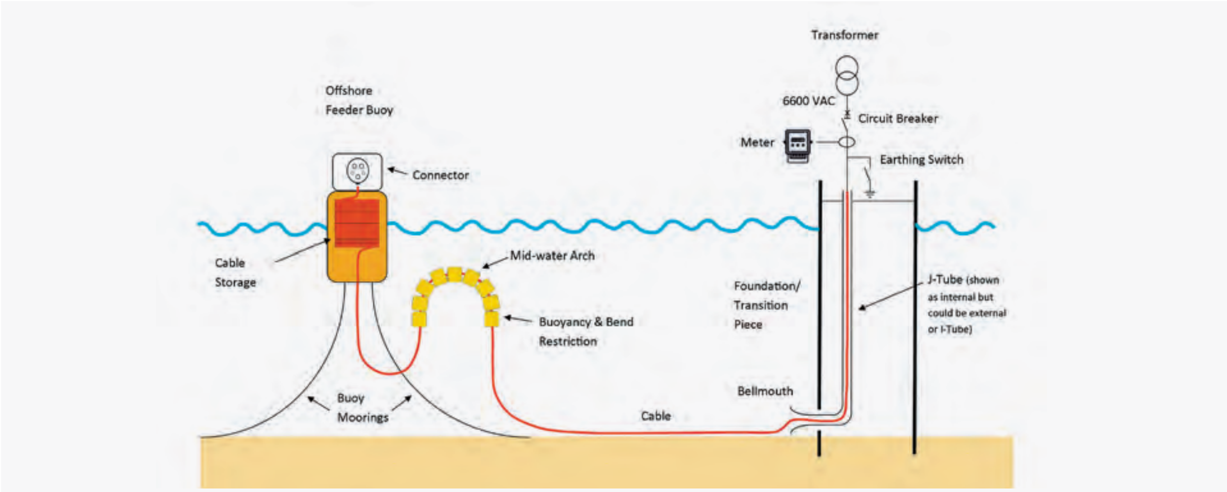


Figure 5.32: MJR offshore electrical charging system – feeder buoy.

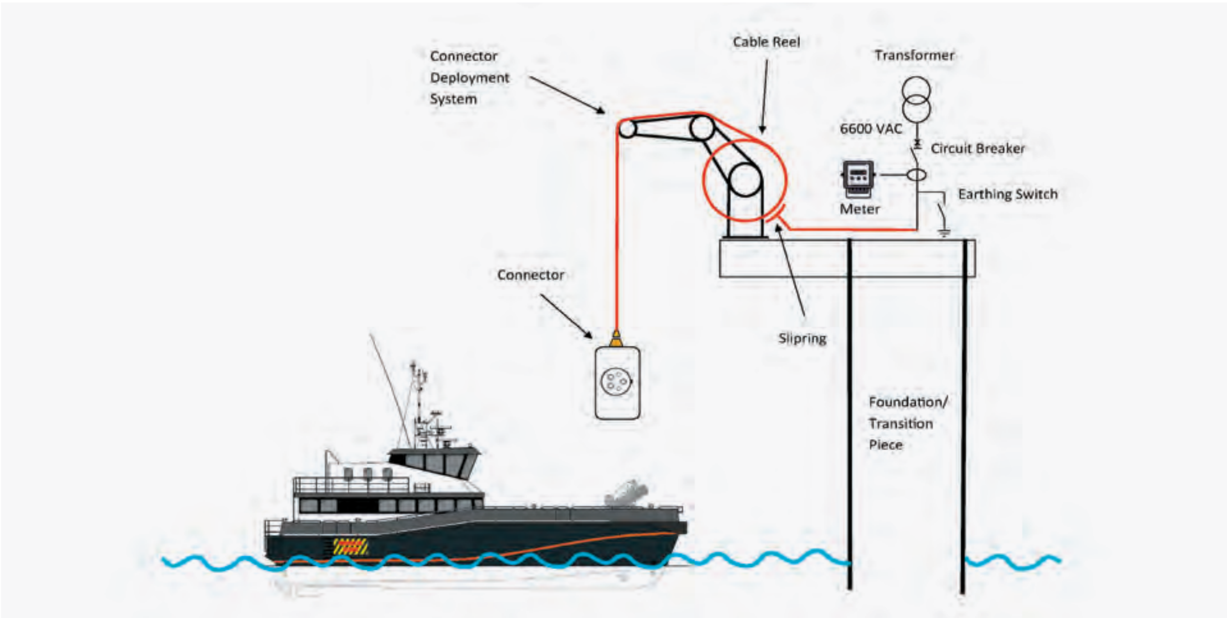


Figure 5.33: MJR offshore electrical charging system – 'in air' solution. Image courtesy of MJR Power and Automation.

There are several advantages to the offshore charging systems shown above, they are manoeuvrable and can be accessed from all sides allowing for different swell direction, easier to maintain than a seabed connector and allow for charging within a wind farm.

The mooring buoy concepts allow for mooring of vessels whilst in field. Meanwhile, MJR's 'in air' solution would offer a lower cost alternative, avoiding any requirement for subsea mooring or cable installation and offering access for all maintenance works without the need for subsea inspection, maintenance or repair.

Before these systems can be made commercially available, a number of key challenges need to be solved. One such challenges is the fact that electrical design capabilities to charge CTV and SOV batteries are still being developed. It has been estimated that 2 MW and 20 MW are required for

CTV and SOV vessels respectively to fast charge in the field with the current connector rating limiting this.

From a market operating perspective, to ensure interoperability, it is important to agree and standardise both the connection interface (between receiving vessel and charging system) and the frequency of the phase supply (50 Hz vs 60 Hz) so that the design can be universal and not specific to an operator or a vessel designer.

Meanwhile, challenges also remain with regard to regulation and metering. None is considered to be insurmountable, but it is important to have regard to the barriers to adoption of this enabling technology.

5.6.4 Energy Islands

The Danish government has agreed to take a majority stake in a £25 billion artificial energy island 80 km off the West coast of Denmark in the North Sea, a first of its kind. This will be the largest construction project in Danish history, the 120,000 m² artificial island is expected to begin construction in 2026 and be finished in 2033. The island itself will be protected from waves and storms on 3 sides with the 4th side having an open dock to allow service vessel access to the island along with the opportunity to recharge and/or refuel from renewable fuel sources created on the island.

In traditional cases, power produced from offshore wind farms are sent to land to be incorporated into the grid. With the design of the energy island, several wind farms can be connected to the island and the energy produced can be either transmitted to land or other neighbouring countries if there is demand. With the electrical energy concentrated in one location it can be used to produce renewable hydrogen and other fuel sources at site when energy production exceeds the grid demand.

The island will initially have a capacity of 3 GW of offshore wind energy, with the ability to expand to 10 GW in the future [94] [95].

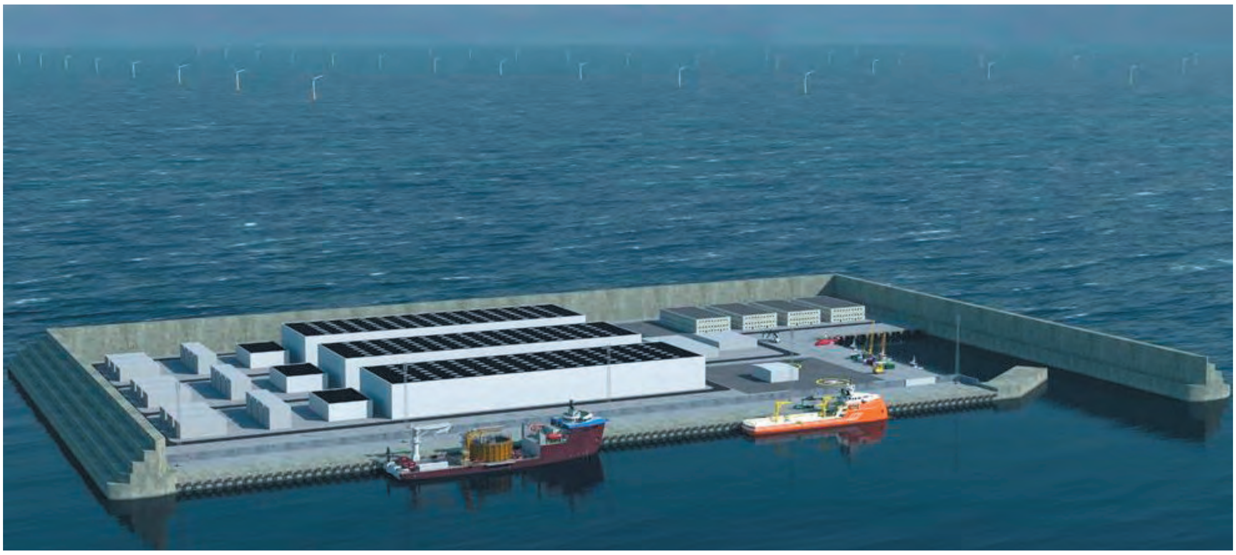


Figure 5.34: Danish energy island hub.

5.7 Autonomous and Remote Operated VesselsA

There are a number of autonomous and remotely operated vessels being developed in the sector building on the success of Aerial (Unmanned Air Vessels) and Marine Subsurface (Remotely Operated Vehicles – ROVs/Autonomous Underwater Vehicles) vessels. As continuous safety improvements and cost reductions are seen as strong drivers to the long-term success of the offshore wind industry, remotely operated and autonomous vessels look to deliver this by relieving humans from unsafe and repetitive tasks. This has the opportunity for autonomous or semi-autonomous vessels to reduce crew in part (or entirely) or allow them to make clearer and better decisions based on the information gathered by the vessel.

A reduction in crew size will have a direct decrease in the size of vessels and power requirements to carry out the work, this leads to less fuel being required to move and power the vessels leading to a reduction in carbon emissions. The hope is that autonomous and remote operated vessels would become more popular and there would be less of a need for larger crewed vessels, thus reducing GHG emissions. It would also see an increase in smaller and fully autonomous vessels which would allow for increased inspection frequencies during O&M activities. This could be done by deploying directly from port or by the vessel living in the field by charging from offshore charging infrastructure. This would result in a reduction in large unplanned maintenance activities, improving uptime and production from working assets.

Below are a few case studies looking at developments in the sector.

Fugro Blue ShadowA

This Uncrewed Surface Vehicle (USV) is used for hydrographic and geophysical surveys. It has been designed for efficiency with a wave piercing hull and structural stability ensuring improved performance in all sea conditions and can operate for days without interruption [96].

Figure 5.35: Fugro's Blue Shadow.

Fugro Blue EssenceA

This USV designed in partnership with SEA-KIT can be used for hydrographic and geophysical surveys as well as inspection and construction support. The vessel offers real time data transfer to the onshore team allowing operators to analyse data and make real time decisions. The Blue Essence is installed with the Fugro's Blue Volta electrical ROV and has the capability to launch and recover the ROV autonomously to aid in the inspection activities. The Blue Volta is an inspection ROV able to operate at a depth of 450 m able to accommodate a number of 3rd party sensors and tools to undertake inspection and repair work remotely [96].

Figure 5.36: Fugro's Blue Essence.

X-Ocean XO-450

XO-450 is a hybrid powered USV vessel driven by solar power, lithium battery packs and a micro diesel engine delivering 3 kW of continuous power. It has been trailed in the commercial environment supplying seabed surveys to 7 of the 140 turbines for Greater Gabbard Offshore Wind Farm in the UK [97].

Figure 5.37: X-Ocean XO-450. Image courtesy of X-Ocean.

iXblue DriXA

DriX is a USV powered by a diesel engine but due to its size and design offers significant reductions in fuel consumption. The design allows for 3rd party equipment to be installed in a gondola 2m under the surface. This allows for noise reduction and a bubble free environment for information to be gathered. The vessel also includes an advanced collision avoidance system and "follow me mode (FMM)" where the DriX will follow its mother vessel at a set distance in open water at high speed (up to 14 knots), actively avoiding collisions and offering high manoeuvrability [98].

Figure 5.38: iXblue DriX.

Key information on the presented autonomous and remote vessels is presented in Table 5-20.

Table 5-20: Summary of autonomous and remotely operated vessels.

Name	Operator	Dimensions LOA x Beam	Max Speed	Engine	Maximum Endurance
Fugro Blue Shadow	Fugro	8.85 x 1.77 m	8 Knots	80 hp diesel engine	Unknown
Fugro Blue Essence	Fugro	11.75 x 2.2 m	4 knots	Electric directional thrust motors	30 days
Fugro Blue Volta	Fugro	1.5 x 0.88 m	3 knots	Electric thrusters	n/a
XO-450	XOcean	4.5 x 2.2 m	4 knots	Hybrid power system 3 kW solar, battery and diesel engine.	18 days or 1,512 nm
DriX	iXblue	7.7 x 0.7 m	14 knots	37.5 hp diesel engine	7 days

5.8 AI and Data Driven Solutions and Tools for Optimised O&M Planning and Marine Coordination

Digital technologies, including Artificial Intelligence (AI) and decision support tools, can play a role in helping the marine sector to meet environmental objectives. Vessel owners, operators and ports are in a position to be able to make data-driven decisions that minimise their costs and environmental impact. By using digital tools, O&M activities can be streamlined and made more efficient.

O&M simulation tools are becoming increasingly common in the offshore wind industry to help optimise O&M strategies and improve asset management.

In order for a vessel, fleet or port to minimise emissions, real-time performance and monitoring data are key. By utilising performance data, that is updated in real time, AI can be implemented across a range of variables that can affect a vessel or ports emissions output. Models can be created that can predict future fuel usage, and emissions, and can impact decision making in O&M operations to inform changes that reduce environmental impact.

Equinor has ambitions to half their maritime emissions in Norway by 2030, and globally by 2050 by using data driven decarbonisation solutions on the approximately 175 vessels it uses [99]. Equinor uses a cloud-based decision management tool for energy efficiency developed by Yxney, called Maress. The software allows a user to visualise energy usage of an operation and to be able to implement initiatives to reduce future energy usage.

The Norwegian NO_x fund collects and records NO_x emissions from all vessels operating in Norwegian waters. Historically this data collection was done manually with every vessel reporting their emissions individually to the NO_x fund. This process was open to having a large margin of error. Recently the fund has adopted the Maress software to implement a digital infrastructure for emission reporting called NO_x Digital. The system will serve as a facilitating tool for helping to reduce emissions.

It is estimated that the 250+ vessels using Maress globally in 2020 will result in an emissions reduction of more than 50,000 tons of CO_2 [100]. A high level schematic of the Maress system can be seen in Figure 5.39.

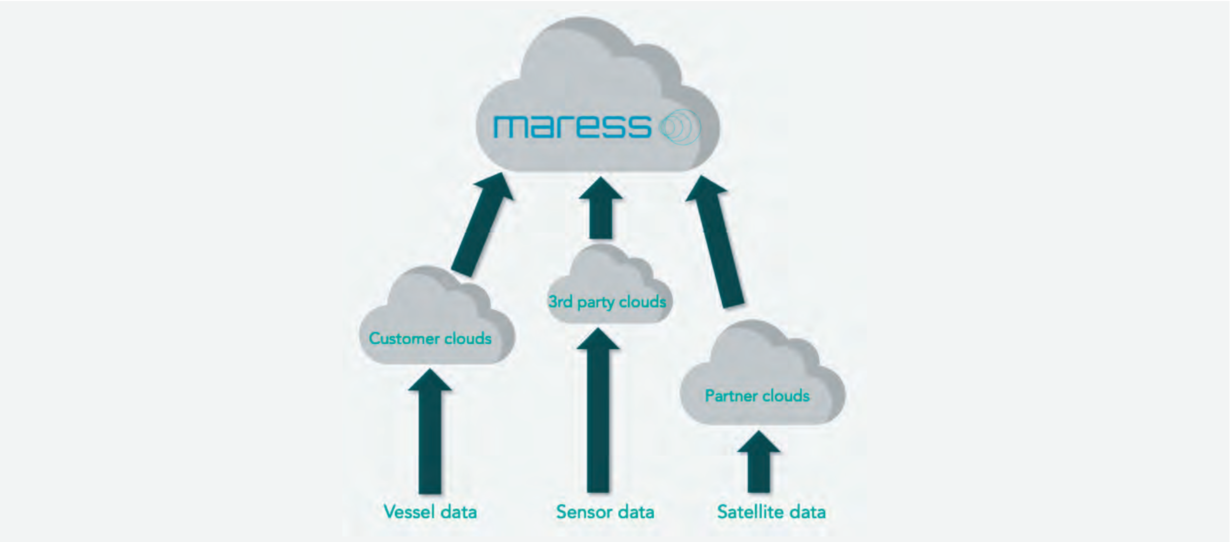


Figure 5.39: Maress system. Image courtesy Yxney Maritime AS.

Ports are also using data driven simulations to look at a port's performance and affecting changes as a result to reduce emissions. The ForeCoast Marine software is a metocean risk management tool owned by JBA. The software is able to simulate a port's operations and how they are effected by metocean conditions. Metocean (meteorology and oceanography) refers to the physical environment both above and below the water line. The system can be used to test how various operational strategies, or changes, to a ports infrastructure will influence performance, and thus aid in decision making in a port's decarbonising plans.

SeaPlanner is a software that includes a suite of tools that combine into a Marine Management System. Offshore wind sites operations, including vessel movements, can be visualised in real-time, enabling changes to be made that can reduce emissions. The software acts as a tool to give key project stakeholders a common operating platform, enabling collaboration across a project. The software is tailored to the specific needs of offshore renewables.

The software can be used to:

- Plan routes and optimise routes in real-time
- Give optimum speeds along the route

- Provide safe weather routing

All of which can have a great effect on fuel consumption and thus emissions.

5.9 Supply Chain Capability and Potential BenefitsA

The transition to clean maritime O&M in North Sea offshore wind will require close cooperation between industry, governments and supply chain. Such a transition presents enormous opportunity but must be managed carefully to ensure that supply chain capability and sustainability are understood and enabled in order to maximise the potential for domestic benefit in terms of growth, job creation and export opportunity.

This report does not attempt to provide a supply chain analysis nor make recommendations for supply chain growth, though it is recommended that performing such an investigation into supply chain capability, opportunities and supporting actions would be extremely beneficial to the UK.

Through the engagement undertaken with multiple stakeholders through the course of developing these findings, the ORE Catapult and the Workboat Association is able to present its understanding of some of the market leaders in terms of market share in some of the key product design, manufacture, build and service areas in clean maritime.

Table 5-21: UK supply chain technology breakdown.

Technology Categorisation		Current Market			
Technology	Sub Group	Market Leaders	Other	Company Location	UK Capability/ potential (P)
Vessel Design, build and operations, including: - Propulsion Systems (new build), - Vessel Retrofit (including hull and propulsion modifications)	**Water Jet**	Hamilton Jet, RollsRoyce, Marine Jet Power		UK, Sweden	
	Fixed Pitch Propeller				
	Forward Facing Propeller	Volvo Penta		Sweden	
	Controllable Pitch Propeller				
	Monohull	Generally conversions			
	Catamaran	Diverse, Damen, AMC, White, Windcat, Northern Offshore Services		UK, Netherlands	Artemis Technologies
	Rigid Inflatable Boats	RibCraft		UK	
	Surface Effect Ships	ESNA		Norway	
	Daughter Crafts	WindPartner, Mare Safety, Tuco		Norway	Delta, Artemis Technologies
	SWATHS	AdHoc		Japan	
	Tri SWATHS	Austals, World Marine Offshore		Australia	
	Foiling Electric Propulsion/System	Artemis Technologies		UK	
	Azimuth Thrusters				
	Manoeuvering Thrusters				
	Voith Schneider Propellers	Voith Schneider		Germany	
	Air Lubricants				
	Selective Catalytic Reduction and Exhaust Gas Recirculation				
	Wind Powering	Artemis Technologies			
	CTV Design	AMC, Chartwell, BMT, Damen, James Walker		UK	Artemis Technologies
	CTV Build	Diverse, Damen, AMC, White, Windcat, Northern Offshore Services		UK	Ali Cat Carmet C Truck Manor PDL Surewind Dales Greenock (P) Infrastrata (Harland & Wolff) (P) SMS Group (P) Artemis Technologies

Technology Categorisation		Current Market			
Vessel Design, build and operations, including: - Propulsion Systems (new build), - Vessel Retrofit (including hull and propulsion modifications)	**CTV Operations**	N-O-S, Windcat, SeaCat, Njord, Cwind, HST		UK	
	SOV Design	Damen		Netherlands	Artemis Technologies
		Ulstein	Wartsila	Norway	
		Vard	RollsRoyce	Canada	
		Havyard		UK	
	SOV Build	Damen		Poland	Infrastrata (H&W - Appledore, Belfast) (P)
		Ulstein		Norway	Fergussons Marine (P)
		Vard	Wartsila	Spain	Cammell Laird (P)
		Havyard		Asia	Peel Ports (P) Malin Group (P)
	SOV Operations	Ostenjo		Norway	
		Esvagt	Deme	Denmark	
		Acta	Windea	Netherlands	
			LDA	Belgium	
			Bibby MS	UK	
			Northstar Renewables		
	Jack-up Vessel Design	Gusto (NOV)		Netherlands	
			Kepple	Singapore	
			Knud e Hansen	Denmark	
			Wartsilia		
	Jack-up Build	Daweoo			
		MHI		Korea	
			Kepple	Singapore	
			KeppleAmfels	USA	
	Jack-up Operations	Seajacks		UK	
		DEME		Netherlands	
		Geosea	Seafox	Netherlands	
		Fred Olsen	Ziton	Denmark	
	Other specialist OSW vessel design/Build				Alnmaritech
					Blyth Catamarans
					Goodchild
					Holyhead Marine
					Lochin
					Artemis Technologies
					Meercat

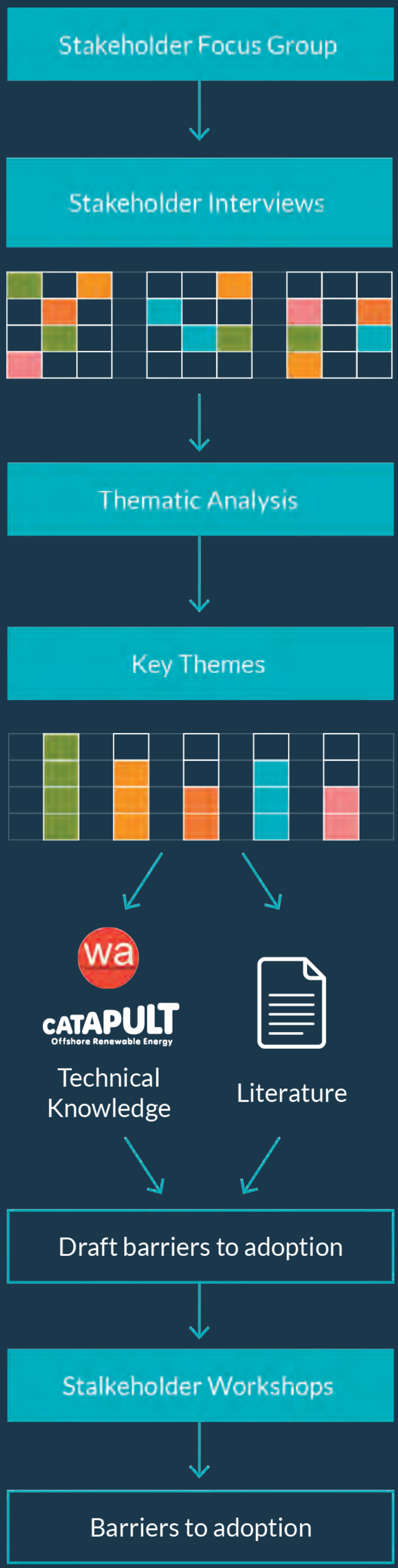
Technology Categorisation		Current Market			
Vessel Design, build and operations, including: - Propulsion Systems (new build), - Vessel Retrofit (including hull and propulsion modifications)	Vessel retrofit/repair/ conversion				MSS
					Falmouth Boat Co
					Dales Yards (others)
					Grimsby Ship Repair
					Peel Facilities (Others)
					Southampton Shipyard (P)
					Global Marine (Falmouth) (P)
					Swansea Dry Dock (P)
					Swan Hunter (P)
					UK Docks Marine Services (Teesside) (P)
Alternative Fuel production and distribution	Hydrogen Production				
	Hydrogen Storage				
	Methanol				
	Di-methyl Ether				
	LNG				
	Ammonia				
	Hydrogen Fuel Cell				
	PEM Electrolysers	ITM			
	Bio Fuels		Goodfuels, Neste	Netherlands	
	Bio Diesel		Goodfuels, Neste	Netherlands	
Electrification, charging systems and batteries	Batteries				Artemis Technologies
	Ionic Flow Batteries		MSE International	UK	
	Shore Charging			UK	Artemis Technologies
	Port Electrification Service Providers				
	Electric Drive Systems			UK	Artemis Technologies
Offshore logistics, operational performance and enabling infrastructure	Offshore E Charging	n/a			MJR, Mara Buoy, AMC
	Offshore Alt Fuelling				
	Voyage planning/ O&M optimisation (Software ML, data and digital)	Shoreline, JBA, Yxney			
	ROV/Autonomous	Fugro, Seakit,			
	Advanced Comms/ cyber security				
	Energy Island				

Technology Categorisation		Current Market			
Port Logistics and enabling infrastructure	**Portside Electrolysers**	CMB,			
	Grid Connection/ energy systems/micro grid	Yara Marine, Vattenfall Networks, SSE Enterprise			
	Shore Power Systems	Cavotec			Artemis Technologies
	Alt Fuel bunkering and distribution				Geos Group (P) Rix (P)
	Onsite Renewables				

Note: This presented supply chain list is not exhaustive and is disproportionately focussed on the UK supply chain.

Whilst many of the enabling actions outlined in this report (Section 7) would likely have an indirect effect in stimulating the clean maritime supply chain, they are not recommendations aimed at direct supply chain development. Further work is recommended to explore UK offshore wind maritime supply chain capabilities, gaps, opportunities and stimulus measures is recommended.

6 IDENTIFICATION OF RISKS AND BARRIERS TO ADOPTION FOR THE DECARBONISATION OF THE SECTOR



6.1 Methodology

In order to determine the barriers to adoption of maritime decarbonisation in the OSW O&M sector a process of industry engagement was undertaken.

Firstly, an industry engagement event was held, where small group discussions were facilitated in order to gain an initial understanding of current feeling about the challenges of decarbonisation.

Feedback from the industry engagement event was used to inform the creation of a questionnaire. The questionnaire consisted of both short closed questions such as assigning scores to the severity of different barriers and longer open ended questions where respondents were encouraged to express their views. Questionnaires were used as the basis for a series of online interviews, generally lasting 1 hour 15 minutes.

A thematic analysis was then conducted on the interview results. Interview transcripts were analysed, with responses coded and gathered into key themes. These key themes were then used alongside the results from the short answer questions to create a report (Appendix 5)

These key themes were then considered, with reference to the literature and input from in-house experts in order to devise a draft list of barriers to decarbonisation. Previously published work by the DfT [101] was used to provide a framework for classifying barriers and they were each assigned accordingly to one of the following categories:

- Economic
- Policy/Regulatory
- Structural
- Organisational
- Behavioural

During assignment, it was noted that many of the barriers could have fallen under a number of categories, but the one deemed to be most fitting was used for each. In accordance with the framework used, each barrier was assigned a rating of either high, medium or low impact (Table 6-1).

These Draft Barriers were then presented at a series of stakeholder workshops to representatives from different sectors of the industry. Representatives were asked for feedback on how well the barriers and ratings reflected their views, and adjustments were made accordingly. From this a final list of risks and barriers to adoption for the decarbonisation of the sector was produced.

6.2 RatingsA

Table 6-1: Impact rating breakdown.

Impact rating	Description
High impact	Uptake is unlikely to increase materially from today's levels unless the barrier is addressed.
Medium impact	Uptake could increase to some extent from today's levels over time but would be more rapid and wide-scale if the barrier is addressed.
Low impact	Uptake likely to increase on its own but addressing barrier will allow more widespread and rapid uptake.

Barrier ratings considered the question, "What effect will this barrier have on progression towards decarbonisation of the North Sea's offshore wind O&M fleet by 2030?".

Initially ratings were assigned based both upon the frequency they were encountered in the industry interviews and the quantitative ratings given by interviewees (where appropriate). These were then considered subjectively based on the wording used by interviewees, in-house expertise and reference to the literature.

Refinement of these ratings was made during a series of industry panels. Barriers and ratings were presented to stakeholders from across 5 industry sectors in order to get feedback. Attendees were asked to vote on various aspects of what was presented, including: barriers missed and barrier ratings they considered inaccurate. Following on from this there was a discussion on what could be changed to ensure the findings reflected industry opinion.

The barriers and ratings included in the final list are categorised and detailed in the following section and then presented in a summary table.

6.3 Economic

6.3.1 Wholesale Cost Differential Between Conventional and Alternative FuelsA

The lower carbon fuel and propulsion sources discussed in Section 5 of this report currently have a higher cost and are relatively expensive compared with fossil fuels. Whilst this is the case the extra operating expenditure of vessels using lower carbon fuels will make large scale take-up unlikely on economic factors alone.

The increased cost can be attributed - to an extent - to them being emergent technologies with cost predicted to reduce once the research and infrastructure to support them develops and production can benefit from economies of scale. During early adoption however, these fuels will not be attractive without intervention which in turn will delay any cost reduction achieved from economies of scale. The class society DNV GL suggest that, "without taxation or subsidies, renewable fuels will find it difficult to compete with the prices of conventional fossil fuels" [102]. Across all five stakeholder workshops "fuel costs" were consistently voted as being one of the biggest barriers to maritime decarbonisation. **This Barrier was rated as being 'High'**.

6.3.2 Disproportionate Carbon PricingA

The effects of burning fossil fuels on the environment and to human health are widely known and publicised but as of now the price of fuels does not currently take this into account. Fossil fuels and fuels derived from them are generally options with the highest emissions yet this is not always reflected in their sales price. In the offshore wind operations and maintenance sector use of marine gas oil (MGO) is ubiquitous. In common with the rest of the world North Sea MGO bunkers do not attract any direct taxation. This is in contrast to electricity, the generation of which – in many North Sea countries - has a lower emissions intensity but incurs carbon taxation in its production and environmental and social levies at the point of sale. Lack of carbon pricing results in a market failure whereby external costs are not factored into fuel choice decisions. [103]

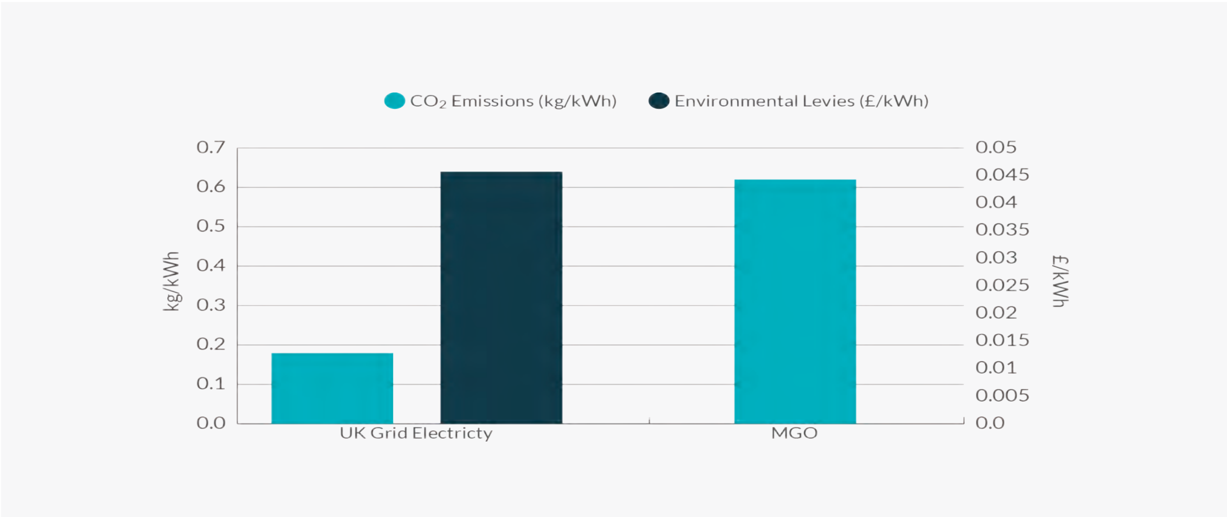


Figure 6.1: Dual axis clustered column graph showing CO_2 intensity and environmental levies for the UK's grid electricity and MGO.

UK road transport has begun to electrify, in part due to the comparatively lower cost of electricity compared to petrol and diesel. The differential is largely driven by duty paid on fossil fuels for road transport. In the maritime sector this relationship is reversed, lower carbon electricity relatively higher cost due to environmental and social obligation taxes, whereas MGO attracts no taxation. In industry interviews with ports and energy infrastructure developers concern was raised that even if shoreside electrical connections were available, vessel operators may continue to use diesel to generate electricity to reduce costs. In a survey by Lloyd's register and UMAS, 75% of shipowners felt that a carbon price on fuels was needed in order to make zero emissions vessels viable [104]. **This barrier was rated as being 'high'**.

6.3.3 Lack of Clarity Over Fuel PathwaysA

Although there is a general consensus that fuel types will need to change to deliver OSW O&M decarbonisation there is no clarity as to which fuel types will dominate. This means that both ports and vessel operators are hesitant to commit to one particular technology en-masse, resulting in market inertia, with reduced take-up until sufficient large scale demonstrations are in place to develop market confidence.

This uncertainty is a clear roadblock to clean technology investment and in interviews was near universally commented upon as one of, if not the major barrier to decarbonisation. Vessel operators were concerned that even if they identified a port that could supply their desired fuel this would then limit their potential market if this fuel was not universally available. Offshore wind industry vessels, and in particular CTVs, are often chartered for relatively short periods (at best perhaps 5 years, down to much shorter 'spot' charters of days, weeks or months) and need to operate from many different ports and for many different clients in different nations over their operational life. This challenge also exists for SOVs though charter periods tend to be longer, typically in the region of 10-15 years. Ports in turn are reluctant to invest in alternative fuel infrastructure if future demand cannot be guaranteed. Several respondents reported that in some cases these barriers can and have been overcome in ports where municipal ownership enables longer-term investment decisions that take greater account of environmental and societal benefits, as opposed to shorter-term ROI imperatives inherent in the investment decisions of privately owned ports. In securing orders for low/zero emissions vessels, uncertainty on power/fuel infrastructure was seen as the greatest challenge amongst vessel designers and builders. Across all five stakeholder workshops "lack of clarity over fuel pathways" was consistently voted as being one of the biggest barriers to maritime decarbonisation. **This barrier was rated as being 'high'**.

See Case Study: R/V Robert Gordon Sproul for an example of lack of fuel availability resulting in stranded assets.

Case study

R/V ROBERT GORDON SPROUL

In 2014, Scripps Institution of Oceanography received a grant from the US Department of Transportation to test the use of biofuel on the research vessel Robert Gordon Sproul. The project investigated the viability of using hydrotreated renewable diesel fuel on a long-term basis.

Over the course of the experiment the vessel conducted 39 oceanographic research and education missions, spanning 89 operational days at sea, covering more than 14,400 nautical miles and involving 527 scientists and students. In the process, the vessel used a total of 52,500 gallons of renewable diesel.

“We were able to show that our existing ship ran as well if not better on biofuel, the hope is that the price of biofuel will come down as the manufacturing process gets better understood, and as people test it and start adopting it. Now that there’s proof of concept, it should be easy to keep doing it.”

R/V Robert Gordon Sproul is once again running on diesel as its biofuel supply ran out in December 2015.

“Biofuel has proven itself to be an ideal renewable fuel source for an academic research vessel, but there’s one slight hitch: it costs about 10 percent more than fossil fuel, and ship costs must be kept as low as possible in order to ensure that Scripps students and the next generation of scientists are given shipboard access. This puts biofuel out of reach for the Scripps fleet—at least for the time being—but that could change with the help of private support or other sources of funding.”

6.3.4 Lack of Knowledge Of Future Fuel And Electricity CostA

Even if operators are confident of fuel supply they will require some confidence over future fuel costs. Demand for low carbon alternative fuels will not come solely from the maritime sector. Other usage sectors such as industry, heating and transport also lack clarity in future fuel mix demand. As supply cannot currently be planned to meet demand this leads to risk of high fuel price volatility. A parallel issue exists for electricity costs where, although supply is set to increase significantly there is a high potential for price volatility dependent on time of use.

In interviews, future fuel supply certainty was seen as a key barrier to the roll-out of clean maritime technologies. Vessel owners and operators need to have certainty, not only that bunkering facilities will be available within ports but that a supply chain will be available in the future that delivers these fuels at a stable price upon which they can budget. Current supply chains are more mature for conventional fuels (such as MGO) and have some maturity for lower carbon fuels (such as LNG) yet are relatively new for zero carbon fuels (such as green hydrogen). This could mean that future fuel price volatility is considered a lower risk for these higher emitting fuels. Although higher demand may be of benefit to production in the long term it could cause price volatility, particularly in an emerging market. In a report by DNV GL the concern was raised, "what would happen if a fuel alternative were to become so attractive that a large number of operators would want to adopt it for their ships within a short period of time". When this was explored they found that, "for all alternative fuels, with the exception of LNG, a rapid rise in demand would require massive investments in production capacity" [102]. **This barrier was considered 'medium'**.

6.3.5 High Capital Cost of Clean Maritime Technologies

Low carbon maritime operations incur high capital costs in technology and infrastructure. Clean technology in new build vessels generally comes at a cost premium and retrofit can be a costly unplanned expenditure. New portside fuelling, storage and fuel delivery infrastructure will be expensive, especially as traditional fuel bunkers look likely to also be required for a number of years.

Lloyds register/UMAS found "a desire for no more than a 10% increase in ship capital costs for ZEVs [Zero Emission Vessels]." Yet, with the exception of biofuels, alternatives came in above this threshold. [104] In securing orders for low/zero emissions vessels, cost was seen as the greatest challenge amongst vessel designers and builders. Across all five stakeholder workshops "High capital cost of clean maritime technologies" was consistently voted as being one of the biggest barriers to maritime decarbonisation.[1] **This barrier was considered a 'high' risk**

6.3.6 Cost of Raising CapitalA

The cost of raising capital itself can be high with large amounts of uncertainty and change in the sector. Although future vessel demand is predicted to be high, risk of stranded assets due to fuel type uncertainty means that zero-carbon vessels are currently considered a risk. Asset owners incurring higher interest rates will inevitably have to pass these costs on to customers, making low carbon alternatives less attractive.

In interviews with maritime energy infrastructure system stakeholders the most frequently discussed topic was the financial risk of investment. Amongst vessel owners, zero-carbon vessels were considered to be a particular risk in the OSW O&M sector. The particular demands of the industry mean that vessels – particularly SOVs – are becoming more specialised and therefore have less opportunity for resale outside of the sector. Stakeholders stated that because the infrastructure is expensive to implement then the servicing fees must be high to account for this. Across all five stakeholder workshops "Cost of raising capital" was consistently voted as being one of the biggest barriers to maritime decarbonisation. **This barrier was considered a 'high' risk**.

1 'High capital cost of clean maritime technologies' and 'cost of raising capital' were initially presented to the workshop audience as a single barrier before being separated as a result of workshop feedback.

6.3.7 Limited Profit Margins AvailableA

One of the successes of offshore wind in the North Sea has been the competitive environment driving down Levelised Cost of Energy (LCOE) through successive CfD auctions. This has however left small margins for any discretionary spending. Any innovative decarbonisation measures that come with significant expenditure could drive operating cost increases, and therefore be unfeasible without some form of support. **This barrier was considered a 'medium' risk**.

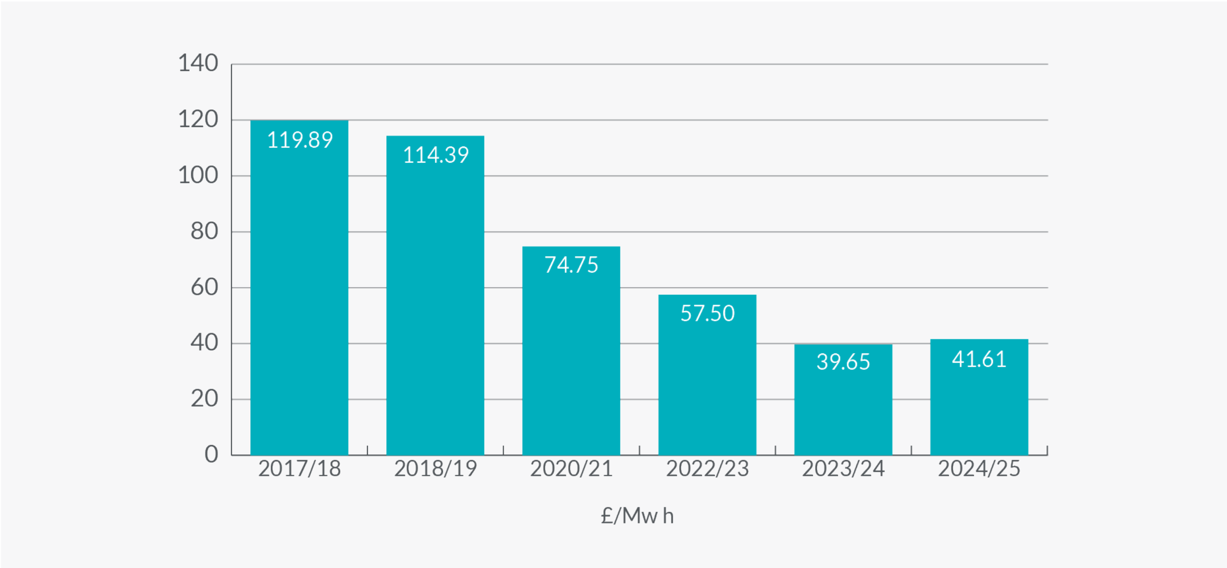


Figure 6.2: Strike price for UK CfD offshore wind projects.

6.4 Policy/Regulatory

6.4.1 Lack of Targets and DeadlinesA

Targets and deadlines allow all stakeholders across the industry to plan for decarbonisation in an appropriate manner. Although clean maritime ambitions across the North Sea are currently high, without firm targets new vessel designs will predominately be optimised to reduce costs in the short to medium term. With firm targets in place, innovation and New Product Development (NPD) cycles can commence in advance with relative confidence of finding a market for the end product.

The need for targets and deadlines, although not universally popular, had widespread acceptance across the industry. Future ambitions and visions were not seen as sufficient basis for organisations to make business plans and investment decisions. Although some organisations were keen to point out that deadlines must be technically achievable it was accepted that binding maritime decarbonisation targets either set by government or agreed between industry should not be solely for the long term and a realistic pathway with targets in the medium as well as long term was best. Those who had expressed a strong desire to decarbonise operations rapidly also saw targets as a means to create a 'level playing field', reducing the risk that competition would undercut them. **This barrier was classed as being a 'high' risk.**

6.4.2 Safety Codes For New Fuels And Marine Electrical Technologies

Safety codes for existing, conventional marine fuels have been in place for many years. Industry has had time to become accustomed to these and develop operational procedures and training around them. Land owners, regulators, class societies and local/national government are familiar with the requirements for these fuels and their storage and distribution systems in terms of planning, permitting and consenting. Safety codes for lower emission fuels and electrical systems are either not finalised or less well established and understood. This results in a number of barriers such as the cost to develop new procedures and training and a disincentive for 'first-movers' who will be reluctant to spend money to overcome any new challenges that will not be necessary for their competitors. In other sectors, such as electrical vehicles, small companies have taken on risks and then been acquired by larger OEMs.

Safety concerns were frequently noted in interviews across the industry. Common concerns included fuel handling and explosive risks in the case of Hydrogen, environmental contamination risk, in the case of ammonia and battery fire risks. Without safety codes operators noted it was difficult to prepare for, quantify and mitigate these risks without investing heavily, an investment that their competitors would benefit from equally. In industry workshops it was raised that although class societies had approved some battery technologies for use, there was a significant time delay in this, resulting in available battery technologies being a number of years behind the cutting edge. Lloyds register noted that there was "Insufficient understanding of hydrogen safety aspects for code development" [104]. In the industry panel this barrier was presented as being high but voting did not reflect this. Workshop attendees felt that although these issues presented difficulties, progress was likely to be fast once sufficient economic incentives were in place to drive demand. **This barrier was considered a 'medium' risk**.

Concept risk assessment of a hydrogen driven high speed passenger ferryA

Study published in ‘International Journal of Hydrogen Energy

Aim:A

Produce a risk assessment of hydrogen ship according to IGF-code Alternative Design Approach.

Vessel Design:A

Medium sized passenger ferry with a capacity of 100 passengers, has a light weight carbon fibre hull, rated speed of 28 knots, hydrogen storage capacity of 450 kg, and installed propulsion power of 1.2 MW. Reference route has a distance of 113 nautical miles per day

Relevant findings:A

- For hydrogen fuel cell vessels no dedicated class rules exist and thus significant extra effort is required to assess safety risks.
- The estimated risk related to hydrogen systems is relatively low, and much lower than the expected acceptable risk tolerance level of 0.5–1.0 fatalities per 10^9 passenger km

[108]

6.4.3 Lack of StandardsA

New fuels and charging systems require unified standards to ensure interoperability. If a large number of connection interfaces, fuel grades, delivery methods etc. are allowed to proliferate then vessel owners will have to either be tied to a reduced number of ports or incur extra costs and weight of installing secondary fuelling/charging systems. Alternatively, ports will have to build extra infrastructure, an endeavour that is likely to be costly and impinge on – often in high demand - portside space.

Interviewees saw a lack of standards as hampering adoption, particularly at the point of refuelling and charging. Large organisations may have the ‘clout’ to develop and drive new standards but smaller operators would take on a higher risk in doing so. This is of particular concern for vessel operators where there are a relatively large number of smaller companies in the marketplace who expressed a desire to adopt new fuel usage but are hesitant to act until standards are adopted that ensure their vessels will not need expensive retrofit. Harmonisation of standards was desired wherever possible but particularly across the North Sea (and Irish Sea) area where many vessel operators saw their market focussed. Port Owner/Operators expressed that the lack of standardisation caused concerns over the security of invested infrastructure. **This barrier was considered a 'medium' risk**.

6.4.4 Imperfect Information About EmissionsA

Without detailed knowledge of current emissions, setting targets for decarbonisation, monitoring progress and comparing technologies is made more difficult. Emissions estimates that do not accurately assess emissions from the production of lower carbon fuels also risk carbon emissions simply being shifted upstream. Furthermore, production of new vessels has an embedded carbon cost, these need to be accounted for as part of a lifecycle emissions accounting approach.

The majority of vessels across the maritime sector are utilised for transport of cargo and passengers between fixed docking points where reasonable emissions estimates can be made from transit speed profiles. OSW O&M vessels often use significant amounts of fuel whilst relatively stationary (i.e. 'pushing on' to a turbine platform). This makes many existing models/approaches for emissions estimates inappropriate for the sector.

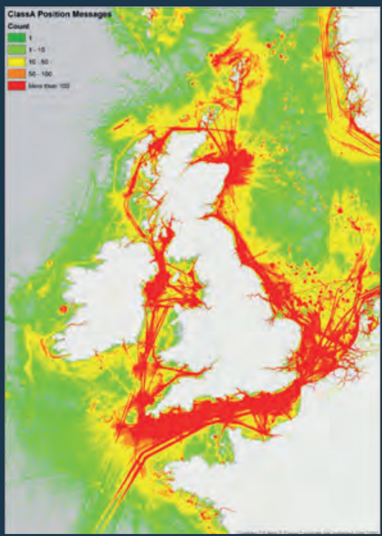
"Several studies have looked at identifying the size of the carbon footprint for offshore wind farms by undertaking Lifecycle Assessments (LCAs). LCAs take a holistic view of the offshore wind farm, including embodied carbon of all materials used on the project. As a result, the vessel emissions incurred during the O&M phase are usually estimated at a high level in these studies. Operations and maintenance of offshore wind farms is complex with many variables and constraints. Therefore, high level assumptions such as these might result in unrealistic estimates of vessel usage." [6]

As part of this project we sought to capture data from current O&M vessel emissions. During the course of the interviews it became clear that there were no standards for recording data across the industry. Although all actors closely involved in vessel operations sought to capture data, the methodology for doing so varied. Although biofuels, hydrogen, ammonia and electricity all have the potential to provide zero emissions energy there was concern amongst interviewees that in reality, production of these fuels would lead to emissions simply being shifted upstream as well as other environmental consequences. **This barrier was considered a 'medium' risk.**

See Case study: UK emissions reporting.

Case Study

UK emissions reporting



The UK reports on its greenhouse gas emissions through the 'National Atmospheric Emissions Inventory' Maritime emissions inventory made up largely of vessels transporting cargo and passengers from port to port and us such is optimised for this. Emissions from individual vessels calculated by tracking ship movements and calculating fuel usage based on averages for various ship types. Currently assumes all vessels use heavy fuel oil or marine diesel oil.

Figure 6.3: Movements of vessels near to the UK tracked by automatic identification system.

6.5 Structural

6.5.1 Existing Port Infrastructure

Vessels have traditionally been fuelled by marine gas oil and the portside infrastructure has been developed to support this. Provision of alternative fuels and shoreside electricity requires significant new infrastructure. Spatial constraints within the port can hamper the development of new technologies.

Many towns have grown around a port and the industry supporting it. Ports operating for many years with a limited number of bunker fuels available will need to find extra space especially if the ports are required to support hydrocarbon propulsion whilst at the same time supporting green technology uptake. Spatial constraints may be even more acute for fuels with low energy densities where low temperatures or high pressures are necessary for storage along with the extra spacing required due to safety considerations. In industry interviews portside facilities for alternative fuel bunkering were considered the most important enabling technology for clean maritime in the OSW O&M sector. In stakeholder workshops the lack of space available in some ports was raised, with particular concern where ports were close to residential areas raising safety concerns and with relation to high land prices close to portside. Although all bunkering fuels come with some degree of risk, the challenges surrounding ammonia and hydrogen may be of particular concern when developing new infrastructure. Participants suggested that municipal port ownership has a positive effect on investment in infrastructure, enabling a longer-term view to be taken on investment return given the social benefit of investments, and that it enables a unified approach between industry, society and government (at either national, regional or local level) to fully support decarbonisation. Across all five stakeholder workshops “Existing port infrastructure” was consistently voted as being one of the biggest barriers to maritime decarbonisation. **This barrier was considered a 'high' risk**.

6.5.2 Portside Electrical Power Constraints

Whether charging batteries or simply running onboard electrical operations without using generators whilst in port (cold ironing), shoreside electrical power is widely seen to be a significant enabler in reducing carbon emissions. As this option becomes more popular, vessels with high power demands and multiple users wishing to access shore power concurrently may be limited by local grid constraints. Many UK ports currently do not have sufficient grid connection to support this load.

Work by the Tyndall centre [91] found that many UK ports do not currently have sufficient grid capacity for high shore-power loads, a problem that could be exacerbated in future if multiple ships wished to connect simultaneously. Furthermore, where ports did wish to add extra capacity this could be an expensive, and administratively difficult process. In industry interviews, ‘cold ironing’ was frequently raised as a key enabler of decarbonisation. For both historical and geographic reasons UK ports often did not have a sufficient grid capacity to supply potential future demand, with the cost of upgrade providing a key roadblock. This issue was particularly acute for smaller port organisations who may not have sufficient staff dedicated to this area. Ports also have to consider neighbours who may share the same connection and themselves have heavy electricity demands such as maritime industrial areas. Port operators report finding the DNO system for navigating grid upgrade approvals as opaque and slow. For larger ports, power requirements may necessitate direct connection to the national grid, which will entail significant costs and infrastructure investments. In industry interviews portside charging facilities were considered the second most important enabling technology for clean maritime in the OSW O&M sector. Across all five stakeholder workshops “Portside electrical power constraints” was consistently voted as being one of the biggest barriers to maritime decarbonisation. **This barrier was considered a ‘high’ risk**.

See Case Study: Barriers and solutions for UK shore-power.

Case Study

Barriers and solutions for UK shore-power [91]

Tyndall Centre for Climate Change Research completed 40 interviews over May to October 2020 with UK port and ship operators, equipment providers, trade associations, regulators, electricity network operators, classification societies and European ports. The report investigated the feasibility of shore power to combat climate change and local air pollution by evaluating the barriers and enabling actions.

A range of barriers were discussed including: Lack of policy support, weak business cases for ports, difficulties for ship owners and operators, grid capacity issues, project complexity, and low prioritisation. Looking specifically at the grid capacity issues, interviewees stated that shore power loads can reach as high as 10 MW per vessel and if multiple vessels berth at the same time the power demands can increase significantly. The relevant power demands are seen as a major barrier for port electrification as these outputs are not supported and require considerable investment.

Case Study

EU Shore-Side Electricity supply regulations [109]

EU directive 2014/94/EU on the deployment of alternative fuels infrastructure sets out responsibilities for ports within the EU to supply shore side electricity.

“Member States shall ensure that the need for shore-side electricity supply for inland waterway vessels and seagoing ships in maritime and inland ports is assessed in their national policy frameworks. Such shore-side electricity supply shall be installed as a priority in ports of the TEN-T Core Network, and in other ports, by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits.”

“Member States shall ensure that shore-side electricity supply installations for maritime transport, deployed or renewed as from 18 November 2017, comply with [EU] technical specifications."

6.5.3 Existing Vessel Lifetimes

Vessels are expensive to build but can have a long lifetime. For owners to recover their investment, they need to operate their assets over a long period of time. This can lead to a technology lag with old vessels powered by hydrocarbon sources operating far into the future even if there are new cleaner and greener cost competitive technologies available on the market. Where vessel retirement is deemed necessary, the financial as well as environmental cost of disposal needs to be considered.

The vessel owners consulted commented that investment decisions could be made based on a vessel lifetime of (at least) 10 years but that service lifetimes can be far in excess of this. This means that vessels being commissioned today will likely still be in the water well beyond 2030. In order for decarbonisation to occur across the fleet it is likely that a programme of retrofits will need to be put in place. This will be a costly endeavour, so it will be beneficial if conventionally fuelled vessels in design today were designed with retrofit in mind. Companies involved in vessel design and construction commented that customers (across the wider maritime sector) were looking for vessels that were 'future fuels ready' but with little clear indication of what this meant in terms of details. **This barrier was considered a 'medium' risk**.

6.5.4 Split Incentives

The ultimate demand for vessels from within the industry will come from the wind farm owner operators and OEMs as charterers. The fuel costs are typically paid by these organisations whereas capital expenditure on vessels and fuelling infrastructure will be initially borne by others. This risks imperfect decision making on new vessel design if vessel operators are incentivised to reduce capital spend as they are less likely to see benefit from operational efficiencies and the lower carbon footprint.

Although CAPEX and OPEX costs are ultimately all paid for by the end user (consumer) the unequal distribution of these costs along the supply chain means that OPEX are generally felt more directly. In industry interviews vessel builders and owners noted that customers were keen to have 'green' vessel technologies but were reluctant to pay the price premium. Suggestions of cost sharing and collaborative approaches were common, as were longer charter lengths. Some research within the maritime sector as a whole however suggests that split incentives are not leading to significant barriers to green technologies [105]. **This barrier was considered a 'medium' risk**.

6.5.5 Charter Lengths

Vessel charter lengths in the industry vary widely, from spot prices to long term contracts. Shorter contracts create investment risk for vessel owners. As the vessel requirements for OSW O&M become more specialised, so the opportunity for vessels to be utilised in different sectors decreases. Without charter lengths of a reasonable duration or confidence in follow-on charters, low carbon vessels become a higher risk investment.

In Interviews many respondents noted that charter lengths were particularly an issue for CTVs where shorter charter durations and spot price charters were common. **This barrier was considered to be a 'medium' risk**.

6.5.6 Fixed Funding for Existing and Under Development Wind Farms

The UK already has a significant number of CfDs in place that will fix energy prices for owner operators for 15 years of operation. Competitive CfD bid prices will have been informed by current understandings of O&M costs. This will mean that there is little funding for increased O&M costs if decarbonisation comes in at a cost beyond current expenditure. This will need to be borne in mind in targets for existing and pipeline wind farms, where fast decarbonisation is likely to require financial support. **This barrier was considered to be a 'medium' risk**.

See case study: Contracts for Difference.

Case study

Contracts for Difference (CfDs)

CfDs are designed to set a fixed price for low carbon electricity generation.

Prospective developers place bids on the price at which they can deliver electrical energy to the grid. The lowest bids are selected and a 'strike price' set (the highest price of the winning bidders). The fund for the CfD mechanism is paid for from consumer electricity bills. Once successful developers begin generating electricity they are responsible for selling to the market. When the market price is below the CfD price the fund pays the difference to the developer. When the market price is above the strike price the developer pays back to the fund.

The scheme aims to give price certainty to developers who are guaranteed a fixed price for their electricity, reducing investment risk. UK consumers are likewise guaranteed a fixed purchase price as balancing payments are ultimately linked to electricity bills.

6.5.7 Effect of Electrical Usage on Wider Electrical Network StabilityA

The offshore wind sector is an integral part of the UK's future electricity supply. Balancing national and regional electrical supply with the demands of multiple off-takers on a time of day basis is one of the key challenges the UK will face in meeting its net zero goals. Some low carbon vessel technologies have the potential to lessen this challenge but only if operational usage is taken into account. Vessels with electrical demand can place strain on local grids (discussed later). However if vessels are connected when not required then grid services can be provided by the battery charging at times when the grid is oversupplied and discharging when wider grid demand is high. Similarly, the synthesis of many low carbon fuels (hydrogen, ammonia, ethanol) involves the use of electrical energy if it is to be considered 'green'. **This barrier was considered a 'low' risk**.

6.6 Organisational

6.6.1 Lack of Horizontal Collaboration Between CompetitorsA

Organisations across the industry need to remain cost competitive. Many low carbon technologies require significant R&D investment and risk. First movers will bare these costs, the benefits of which are potentially shared between competitors. Horizontal collaboration can de-risk these investments by ensuring that investment is spread between competitors. Furthermore, it can help ensure compatible standards across the industry.

Some industry interviewees highlighted further industry collaboration was necessary to support expedited decarbonisation. There was a feeling that any one organisation that acted first would incur greater costs which would not be present for later adopters. There were also positive reports that industry collaboration is happening already but that further integration on joint projects would be beneficial particularly where high-risk capital was at stake. **This barrier was considered a 'medium' risk**.

6.6.2 Lack of Vertical Collaboration Along the Supply ChainA

Collaboration between clients and potential providers can help foster innovation. R&D and demonstrations at scale can benefit from input from a variety of different component and systems manufacturers in order for designers to be able to better assess the capabilities and limitations of the latest technologies. Furthermore, vertical collaboration can help to spread risk along the supply chain so that investment costs are spread between those likely to benefit from the end product.

In interviews, vessel designers and operators talked about the need to adopt a holistic approach, with communication between clients and suppliers pre-procurement, helping both parties spec appropriate technologies to vessel requirements. Comments across the industry noted that there were already good examples of collaboration but furthering this would be a benefit. **This barrier was considered a 'medium' risk**.

See case study: Floating Offshore Wind Centre of Excellence.

Case study

Floating Offshore Wind Centre of Excellence

Mission

Drive the commercialisation of floating offshore wind for the UK's benefit – through a reduction in the UK's carbon emissions and an increase in economic Gross Value Added (GVA).

ObjectivesA

- Establish the UK as the leading floating offshore wind (FOW) market in the world
- Establish an internationally recognised centre of excellence in FOW
- Reduce the levelized cost of energy from FOW to a commercially manageable rate
- Cut back development time for FOW farms
- Develop opportunities for the UK supply chain
- Attract investment in FOW research and development in the UK

Partners

Industrial, academic and supply chain partnerships including:

Copenhagen Infrastructure Partners, EDF Energy, equinor, ESB, Green Investment Group, Northland Power, Mainstream Renewable Power, Ocean Winds, RWE, Scottish Power Renewables, Shell, SSE Renewables, Total. [7]

6.6.3 Structure of Offshore Wind Farm Asset Ownership and Governance

Many wind farm developers have, or at least have had in the past, a tendency to divest a proportion of the offshore wind farm asset upon one of several key project milestones (including consent, FID, first power or beyond). This divestment of a proportion of the asset has supported developer cashflow to enable a continuous pipeline of development of new sites.

This means that many of the North Sea's offshore wind farms have complex ownership structures with multiple investors holding a stake in Special Purpose Vehicles (SPVs) as the legal entity established to own and operate the wind farm.

This requires governance arrangements for joint ownership and can introduce complexity to the decision-making process regarding ongoing operational and commercial management of the wind farm. This complexity of decision-making means that in some cases not just one, but rather multiple owners of the wind farm would need to be in agreement before making any decision to adopt clean maritime technologies if there is a cost implication to doing so.

Many partially divested assets and multi-owner governance arrangements can make risk-based investment decisions difficult. **This barrier was considered a 'medium' risk**.

6.6.4 Lack of in Field Performance DataA

There is a lack of 'in field' zero emissions vessels in deployment. Although an increasing number of vessels employ hybrid propulsion systems combining new low emissions technology with fossil fuels there are currently no fully zero emissions vessels in operation. Although zero emissions technology has had considerable R&D, the lack of real-world operations data means that there is still considerable risk associated with solely zero emissions technology. In order to design new vessel systems to maximise efficiency, good knowledge of operating requirements is essential in order to specify fuel/electricity systems that are able to deliver the required power and range. Interviewees noted that vessel operators often did not have good historical data of actual operational usage and therefore were unclear about future demands. This leads to a risk that alternative fuels and batteries may be disregarded as viable options for fear of not providing operational requirements. It was noted that this was a bigger problem for older vessels with many newer vessels incorporating more sophisticated data monitoring systems. **This barrier was considered a 'medium' risk**.

See case study: SPARTA.

Case Study

SPARTA

SPARTA is a joint industry project, established in 2013. The joint venture provides performance benchmarking for operational offshore wind farms. By analysing a range of offshore wind farm data, owner operators are able to plan strategically and make better decisions. SPARTA provides insight on the frequency, total downtime and lost production specific to downtime causes, this enables organisations to compare their wind farm on factors such as turbine and blade type.

6.7 Behavioural

6.7.1 Bias Towards Existing TechnologyA

Biases within the decision-making process can lead to new greener technologies being cast aside in favour of "if it's not broken, don't fix it" mentalities. Vessel owners may be reluctant to invest in cleaner and greener technologies as the benefits of the investment would be seen by the wind farm operators in reduced fuel costs (the standard model is for wind farm owner operators to pay vessel fuel costs) and not necessarily by the vessel owner. **This barrier was considered a 'low' risk**.

6.7.2 Balancing Emissions Reductions Against Minimising Turbine DowntimeA

Offshore wind O&M sits within a sector that will play a large part in driving decarbonisation more widely. Options for reducing emissions include reducing vessel speeds and reducing actual demand for vessel usage. Although emissions reductions gains could be significant in this area this needs to be quantified against any risk of limiting offshore wind output as this will cause a knock-on effect of generating larger emissions from reduced abatement as well as not being economically feasible. **This barrier was considered a 'low' risk**.

6.8 Summary

In the Table 6-2 all barriers are listed with ratings and suggested enabling actions to address these barriers are discussed in Section 7.4.

Table 6-2: Barrier breakdown with linked ratings and enabling actions.

Category	Barrier	Rating	Enabling Actions
Economic	Wholesale cost differential between conventional and alternative fuels	High	1-3
	Lack of clarity over fuel pathways	High	4
	Lack of knowledge of future fuel cost	Medium	1-3
	Limited profit margins available	Medium	1-3
	Disproportionate carbon pricing	High	5
	Capital cost of clean maritime technologies	High	1-3
	Cost of raising capital	High	1-3
Policy/Regulatory	Safety codes for new fuels and electrical technologies	Medium	6
	Lack of standards	Medium	7-9
	Lack of targets and deadlines	High	10-11
	Imperfect information about emissions	Medium	12
Structural	Existing port infrastructure	High	13
	Portside electrical power constraints	High	13
	Existing vessel lifetimes	Medium	2 & 8
	Split incentives	Medium	14
	Charter lengths	Medium	15
	Fixed funding for existing and under development wind farms	Medium	1 & 2
Organisational	Lack of horizontal collaboration between competitors	Medium	17
	Lack of vertical collaboration along the supply chain	Medium	17
	Structure of offshore wind farm asset ownership and governance	Medium	17
	Lack of in field performance data	Medium	16
Behavioural	Bias towards existing technology	Low	
	Balancing emissions reductions against minimising turbine downtime	Low	

7 ROUTE MAP

Having undertaken extensive industry engagement to identify and verify a comprehensive list of barriers to the accelerated adoption of clean maritime technologies, it is important to consider the approach to addressing these barriers.

There are many examples of now thriving industries which at some point in their formation, emergence and growth phases have required interventions from governments, industry, regulators or other stakeholders to provide the environment for growth.

Such interventions are often only necessary for a finite period during the industry's emergence phase when costs of novel technologies and infrastructure upgrades are inevitably high because the economies of scale that come with industrialisation and large scale production/manufacture have not yet been realised.

There are many examples of the impact that short-term intervention can achieve in stimulating growth and enabling the development of thriving and sustainable industries which bring jobs, economic growth, environmental and other social benefits. Offshore wind, Solar PV and Electric Vehicles all serve as examples of industries which have enjoyed significant support from governments and stakeholders in their emergent phases and which have gone on to achieve significant cost reduction, now operating as sustainable growth industries and offering major economic and social benefits that far outweigh the cost of earlier interventions.

Through engagement with industry and drawing on prior research, a 'Roadmap' has been developed which outlines actions that could be taken in combination to help drive the accelerated adoption of clean maritime innovation in offshore wind O&M in the North Sea.

Through adoption of these measures we believe that the North Sea offshore wind industry will be supported to achieve a vision of clean maritime operations in O&M, in turn acting as a springboard and providing stimulus to the development and growth of a nascent clean maritime industry in the North Sea, including many of the UK's maritime clusters.

The Roadmap for the UK to accelerate the decarbonisation of the North Sea offshore wind O&M fleet is set out as four tracks. These tracks will engage the research community, a broad range of industry actors from manufacturers to energy project developers to engineering and service companies, and other key stakeholders from government, class societies regulatory agencies, investors and local communities.

Track 1 is an assessment of technologies. Track 2 is a R&D programme based on the innovation elements that have been identified in Track 1. Track 3 is a set of key demonstrations of critical technologies and integrated systems and markets, at scale. Track 4 is a set of enabling actions, to unblock and accelerate innovation, and support market growth. These tracks aim to address the risks and barriers that were identified in Section 6.

1 Technology assessment

- Assessment of technologies that can accelerate the decarbonisation of the North Sea.
- Technology assessment criteria include:

Technical Opportunity
- Criticality to decarbonisation
- Start and target TRL
- Start and finish date

Market Opportunity
- Size of Opportunity
- Market Spillover

Policy Response and Intervention
- UK Strategic potential - Trade, manufacturing & Export
- UK Strategic potential - IP
- Case for Intervention

2 Core R&D programme

- Delivered through a hub programme structure.
- Short-term 'upscaling' of lower risk current technology and disruptive, higher risk projects.

CAPEX / OPEX reduction

Improve efficiency

Increase manufacturability

Automation and digitalisation

Other

3 Demonstrations at scale

- Demonstrations at scale are an essential means of validating the robustness of new technologies.
- De-risk and drive private sector confidence to invest alongside the public sector in the innovation journey.
- Enable development of approaches to standards, certification and market mechanisms during demonstration.
- Public support for demonstrations at the right scale, and at the right level of technology maturity frequently make the difference between success and failure, for an innovative company.

4 Enabling actions and policies

- Enabling actions include the actions that could be taken by government, regulators or industry to address previously identified barriers (market / policy / regulatory).
- Potential interventions and present thinking that can have a positive impact on identified high and medium level risks.

Figure 7.1: Roadmap tracks.

7.1 Track 1 – Assessment of Technologies MethodologyA

Track 1 assesses different technologies that can accelerate the decarbonisation of the North Sea. These range from green hydrogen production to remotely operated vessels. These innovations have varying potential to improve enabling factors such as improved costs or lifetime of the device.

To accommodate the broad range of technology enablers, a flexible technology assessment and prioritisation methodology has been developed. For each technology, details and scores are provided and explained in Table 7-1.

Table 7-1: Technology assessment criteria.

Criteria	Explanation	Scores
How developed is it and when needed		
Start and target TRL	Technology Readiness Level at the start and end for this technology at timescales provided. Level, defined for a technology, as applied in this sector/situation	TRL 1 to TRL 9 Detailed explanation of TRLs can be found in Appendix 3
Start and finish date	When the significant progress for this technology is expected to start and finish. What date is this technology needed by	Year
Technical Opportunity		
Criticality to decarbonisation	Technical impact on the system of acting/ not acting. How critical this technology is for decarbonising the North Sea	**0** – Alternative technology available **1** – Minimal system performance limiting gain only **2** – Significant system performance limiting gain **3** – System stop
Market opportunity		
Size of Opportunity	How big is the market for this technology? Market limited to North Sea, values are expressed in annual terms (£)	**0** –<£100m market size **1** – £100m-£250m **2** – £250m-£500m **3** – £500m+
Market Spillover	Will the technology be applicable elsewhere outside of the industry covered by this roadmap?	**0** – Technology has no known applicability in other markets **1** – Limited known applicability **2** – Well known applicability, may be early markets **3** – Multiple established alternative markets
Policy Response and Intervention		
UK Strategic potential - Trade, manufacturing & Export	How well placed is the UK supply chain to produce and deliver this technology?	**0** – High volume/low value, limited relevance to UK **1** – High value products & services, 1-2 UK suppliers already **2** – High value products & services, 3+ UK suppliers already **3** – High value products & services, 5+ UK suppliers already
UK Strategic potential - IP	How well placed is the UK to play a role in the development and maturing of the specific technology and benefit from the outcomes?	**0** – No known active commercial players, unknown if uni research **1** – 1-2 commercial players, some evidence of research base **2** – 3-5 commercial players, Wide network of researchers **3** – 5+ commercial players, Worldwide research leader
Case for Intervention	What is the probability that industry would not take this technology forward without additional support? In the high case for intervention, the industry on its own may hit this roadblock and not move forward without government support either through economic or policy mechanisms.	**0** – None – Technology will progress without any support e.g. it's related to company's IP or is already commercially driven. **1** – Low – Technology could progress without support but some delays might occur or benefits will not be captured in full. **2** – Medium – May progress without support – delays will occur or costs will be higher. **3** – High – No progress without support - significant delays will occur or costs will be significantly higher.

The definitions of "low, medium, high" were kept broad and flexible enough to return scores that were comparable across a wide range of technologies.

All challenges with their time to market, current TRL and scores are shown in Table 7-2:

7.2 Track 1 – Technology Assessment ResultsA

Table 7-2: Technology assessment results.

Number	Technology/ Challenge	How developed is it and when needed		Technical Opportunity	Market opportunity		Policy Response and Intervention		
		Start and target TRL	Start and finish date	System Criticality	Size of Opportunity	Market Spillover	UK Strategic potential – trade, manufacture and export	UK Strategic potential - IP	Case for Intervention
1	**Green hydrogen production**	8 and 9	Now and 2030	2	3	3	3	2	2
2	**Blue hydrogen production**	6 and 9	Now and 2028	2	3	3	2	2	1
3	**Methanol production**	6 and 9	Now and 2030	1	3	3	1	2	2
4	**Ammonia production**	6 and 9	Now and 2030	1	3	3	1	2	2
5	**High density hydrogen storage**			3	1	3	2	2	2
6	**High density battery storage**			2	2	3	2	2	2
7	**Offshore electric charging**	6 and 9	Now and 2023	3	1	2	1	1	3
8	**Environmentally sustainable battery production and end-of-life management**	7 and 9	Now and 2030	1	0	3	1	2	3
9	**Autonomous and remotely operated vessels**	4 and 9	Now and 2031	1	2	3	3	3	2
10	**Guidance and standards for fuel handling and storage**	n/a	Now and 2025	3	0	3	n/a	1	2
11	**Guidance and standards for green vessel design and certification**	n/a	Now and 2025	1	0	3	n/a	1	2
12	**Data-driven solutions for emission reduction**	7 and 9	Now and 2025	1	0	1	2	2	1

1 Green hydrogen production

- Proven technology at small scale, but currently not commercially feasible.
- Envisaged to be a critical part of the UK's net zero target. However, alternative fuels for vessels in development.
- Significant potential for hydrogen to be used in transportation, residential and industrial heating, power generation, energy storage and as a feedstock.
- Active development of technology in the UK, including a leading electrolyser manufacturer.

2 Blue hydrogen productionA

- A number of prototype demonstrations in development, but currently not commercially feasible.
- Important solution in short- to medium-term whilst waiting on green hydrogen technology to become cost competitive.
- Significant potential for hydrogen to be used in transportation, residential and industrial heating, power generation, energy storage and as a feedstock.
- Crossover with the UK's O&G industry

3 Methanol production

- Methanol production from renewable hydrogen has received significant attention for years and has reached commercial stage in some areas or sectors.
- Particular attention must focus on the sourcing and managment of CO_2 to remain carbon neutral or even carbon negative.
- Dehydrogenation is done via reforming under pressures and temperatures of c. 200°C. Hydrogen recovery from dimethyl ether is performed through reforming.

4 Ammonia production

- Ammonia production via renewable hydrogen is receiving increasing interest as costs of renewable electricity drop.
- Conventional ammonia production via the Haber-Bosch process must be adapted for proper integration with renewables.
- Ammonia cracking is done in the presence of a catalyst and can possibly generate back pure hydrogen.
- Innovative processes for hydrogenation (e.g. electrochemical) and hydrogen carriers cracking/reforming must be developed.

5 High density hydrogen storage

- A number of technologies in development.
- Without high volumetric density storage solutions hydrogen adoption in offshore wind vessels is unlikely.
- Significant potential for use in transportation and aviation.

6 High density battery storageA

- A number of different technologies are in development.
- Significant potential for use in transportation, energy storage and aviation.
- A number of research activities into different battery technologies, including for use in marine environment, ongoing in the UK.

7 Offshore electric charging

- A number of different technologies for CTV and SOV are in development.
- Without offshore charging, fully electric offshore wind vessels are unlikely to be developed.
- Technology could be deployed in shipping, fishing, recreational vessels and by the MoD.
- Technology developed independently from battery technology. With the first demonstration prototypes having limited commercial use, the case for intervention is high.

8 Environmentally sustainable battery production and end-of-life managementA

- Whilst not critical to reducing emissions in offshore wind vessels, if not considered, there is a high probability of offsetting emission reduction up and down the lifecycle of battery technology.
- End-of-life management of batteries is equally applicable to other technologies and industries such as communications and electric vehicles.

9 Autonomous and remotely operated vessels

- A large number of different types of systems are in development.
- Large potential for technology deployment outside offshore wind e.g. MoD, O&G, environmental research.
- A number of technologies still in early stages of design leading to high case for intervention.

10 Guidance and standards for fuel handling and storage

- Limited to no specific guidance or standards exist on handling and storing low/zero carbon fuels.
- Development of guidance and standards will help to de-risk the technology and drive cost reduction.
- Applicable to other industries e.g. shipping, fishing, recreational vessels and by the MoD.

11 Guidance and standards for green vessel design and certificationA

- Limited guidance and standards for green vessels.
- Development of guidance and standards will help to de-risk the technology and drive cost reduction.
- Applicable to other industries e.g. shipping, fishing, recreational vessels and by MoD.

12 Data-driven solutions for emission reductionA

- A number of solutions in active development are already available on the market. However, the area is yet to be fully explored to both reduce O&M costs, but also to consider emission reduction.

7.3 Track 2 – R&D ProgrammeA

The assessment criteria used to select R&D priorities should form the basis of the objectives for the wider R&D programme. Objectives and example challenges are summarised in Table 7-3:

Table 7-3: R&D programme objectives with example challenges.

	R&D programme objectives	Description	Examples of related technologies
1	**CAPEX reduction**	Reducing the use of high-cost materials; simplifying design to reduce labour and increase automation.	1 Green H_2 production 2 Blue H_2 production
2	**Improve efficiency**	Improve efficiency of vessels operations, tanking/charging speed and efficiency of battery operations.	3 High density hydrogen storage 4 High density battery storage 5 Offshore electric charging
3	**Increase manufacturability**	Low carbon vessels and associated components and supporting infrastructure are currently not manufactured at scale. Continuous serial production methodologies have to be established. Manufacturing equipment will be required that can handle even larger structures at low cost.	1 Green H_2 production 2 Blue H_2 production
4	**Automation and digitalisation**	Developing autonomous and remotely operated systems.	9 Autonomous and remotely operated vessels 12 Data-driven solutions for emission reduction
5	**Other**	Challenges not covered by other objectives.	

This R&D programme could be delivered through a hub programme structure and would consolidate and build on existing research and industrial capabilities in the UK. It would include both short-term upscaling of lower risk current technology and disruptive, higher risk projects.

Case Study

Offshore Wind Innovation Hub

Offshore Wind Innovation Hub

The Offshore Wind Innovation Hub (OWIH) is a programme to coordinate UK innovation activities in the offshore wind sector. Funded by Innovate UK and BEIS, ORE Catapult runs the Innovation Hub in partnership with the Knowledge Transfer Network. It was set up in 2017 to maximise the impact of investment in offshore wind innovation to reduce LCOE, increase UK content, strengthen exports by increasing coordination and collaboration amongst industry and with public funders. This has been critical to accelerate UK supply chain knowledge and innovation impacts.

OWIH does that by providing the government and industry with a primary validated source of information on the key challenges and priorities within the sector. It also aims to increase UK content and contribute to LCOE reduction by monitoring progress in technology innovation and developing a clear, tangible roadmap of activities & priority areas.

7.4 Track 3–Demonstrations at ScaleA

Demonstrations at scale are an essential means of validating the robustness of new technologies and approaches, and encouraging the private sector to invest alongside the public sector in the innovation journey. Public support for demonstrations at the right scale, and at the right level of technology maturity, frequently make the difference between success and failure, for an innovative company.

Some of the high rated barriers listed in Section 6 will have to be addressed through policy interventions and demonstrations. Publicly supported demonstration projects would also bring down the wholesale cost difference between conventional and alternative fuels. They would also decrease the first mover capital cost of clean maritime technologies. Mitigating the high risk of portside electrical power constraints will require support for large scale projects.

Industry representatives during engagement activities stated that need for widespread fuelling infrastructure was seen as the most pressing concern in the roll-out of clean maritime technologies, this applied to all low carbon fuels as shown in Figure A5-9. Deployment could be driven by some of the benefits that were obtainable from offshore electric charging e.g. allowing SOVs to stay at sea longer and act as charging docks for smaller vessels. Table 7-4 summarises suggested demonstrations at scale

See Case Studies: Dutch master plan for an emission-free maritime sector and Clean maritime demonstration competition

Table 7-4: Demonstration list highlighting the related technologies.

Category	Demonstration	Related technology
Offshore logistics, operational performance and enabling infrastructure	Offshore electrical charging stations – available for wind farm service vessels	7 Offshore electric charging
	Offshore alternative fueling – available for wind farm operator and for commercial use (shipping, fishing, recreational vessels)	1 Green H_2 production 2 Blue H_2 production
	Voyage planning and O&M optimization software (including machine learning) to be trialed on a large-scale commercial wind farm	12 Data-driven solutions for emission reduction
	Remotely operated vessels to undertake marine logistics transfer trials	9 Autonomous and remotely operated vessels
	Advanced communications infrastructure	12 Data-driven solutions for emission reduction
	Energy Islands	
Port logistics and enabling infrastructure	Portside electrolysers	1 Green H_2 production 2 Blue H_2 production
	Alternate fuel synthesis	3 Ammonia production 4 Methanol production
	Integration projects to test micro grid within the port	
	Shore Power Systems	
	Alternative fuel bunkering and distribution	10 Guidance and standards for fuel handling and storage

Case Study

Dutch 'Masterplan voor een emissieloze maritieme sector' (Master plan for an emission-free maritime sector)

- Initiative led by KVNR (The Royal Association of Netherlands Shipowners)
- Aims to accelerate the long term greening of Dutch shipping with 30 pilot emissions free vessels and 5 retrofits.
- The sector is looking to finance 75% and seeking €250 million from government/ EU funding.

Technology research
System transition
Methanol
Hydrogen
Modular power
Fuel cell power
Smart monitoring
Autonomous operations

Vessels
Dutch Navy
Rijkswaterstaat (Government Agency)
Civil ships (Wind farm maintenance, fishing, transport (cargo), transport (passenger), inland vessels, work ships
Retrofit of 5 commercial ships
Applying energy-saving technology

Translated and abridged from Nederland Maritiem Land

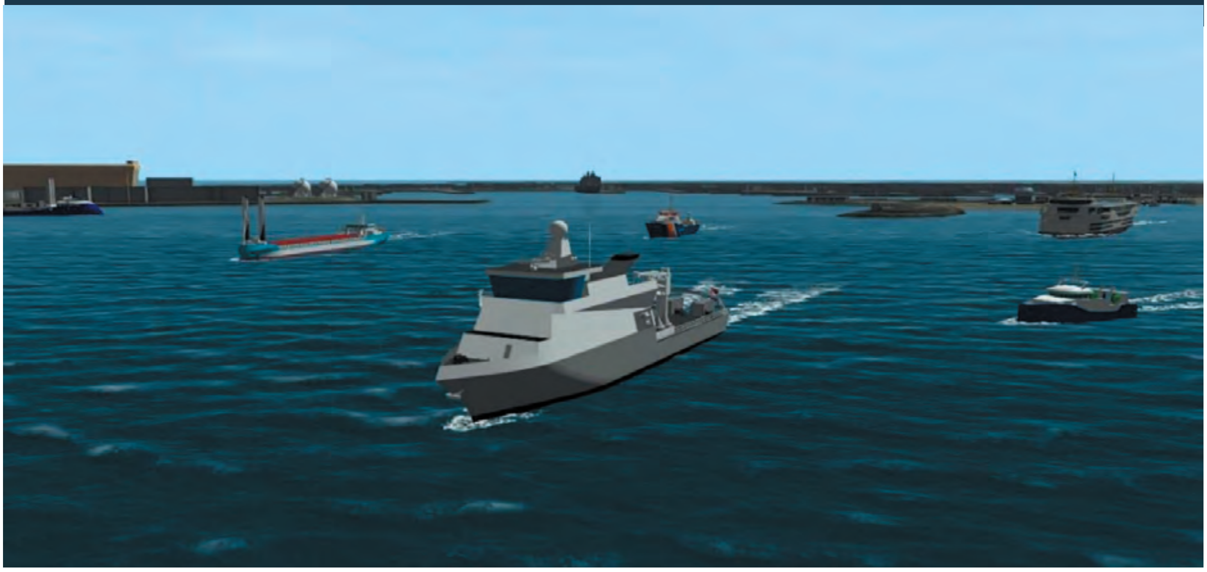


Figure 7.2: Graphical representation of ships potentially within scope of 'Masterplan voor een emissieloze maritieme sector'.

Case study

Clean maritime demonstration competition

- Announced in November 2020 as part of Prime Minister's 10 Point Plan for a Green Industrial Revolution.
- £20m grant funding competition to enable the development and commercialisation of mid-TRL clean maritime technologies.
- One-year programme to support a raft of feasibility studies and demonstrations which will set out investment-ready projects for future government or private sector investment.
- CMDC funding will be reserved to UK-based organisations and will welcome UK wide applications, supporting projects from across the country.

Aims

- Promote deployment of clean maritime technologies and zero emission vessels – putting UK maritime sector at forefront of a global green industrial revolution.
- Support feasibility studies to provide blueprint for a network of projects/places ready for future investment.
- Identifying which technologies are best suited to different operational scenarios, to support market and policy development.

7.5 Track 4– Enabling ActionsA

Achieving decarbonisation of vessels set in scenarios in Section 4 will require mitigating risks listed in Section 6. Track 4 consists of enabling actions - potential interventions that could be taken by governments, regulators or industry. The enabling actions presented here are based on findings from the industry engagement and research set out in the report's methodology.

7.5.1 Enabling Actions to achieve the 'moderate scenario

In order to achieve the moderate scenario we suggest that all 'high' level risks will have to be addressed. This would allow the industry to achieve decarbonisation of CTVs and SOVs by 23% in 2025 and by 48% in 2030 as shown in Figure 7-3.

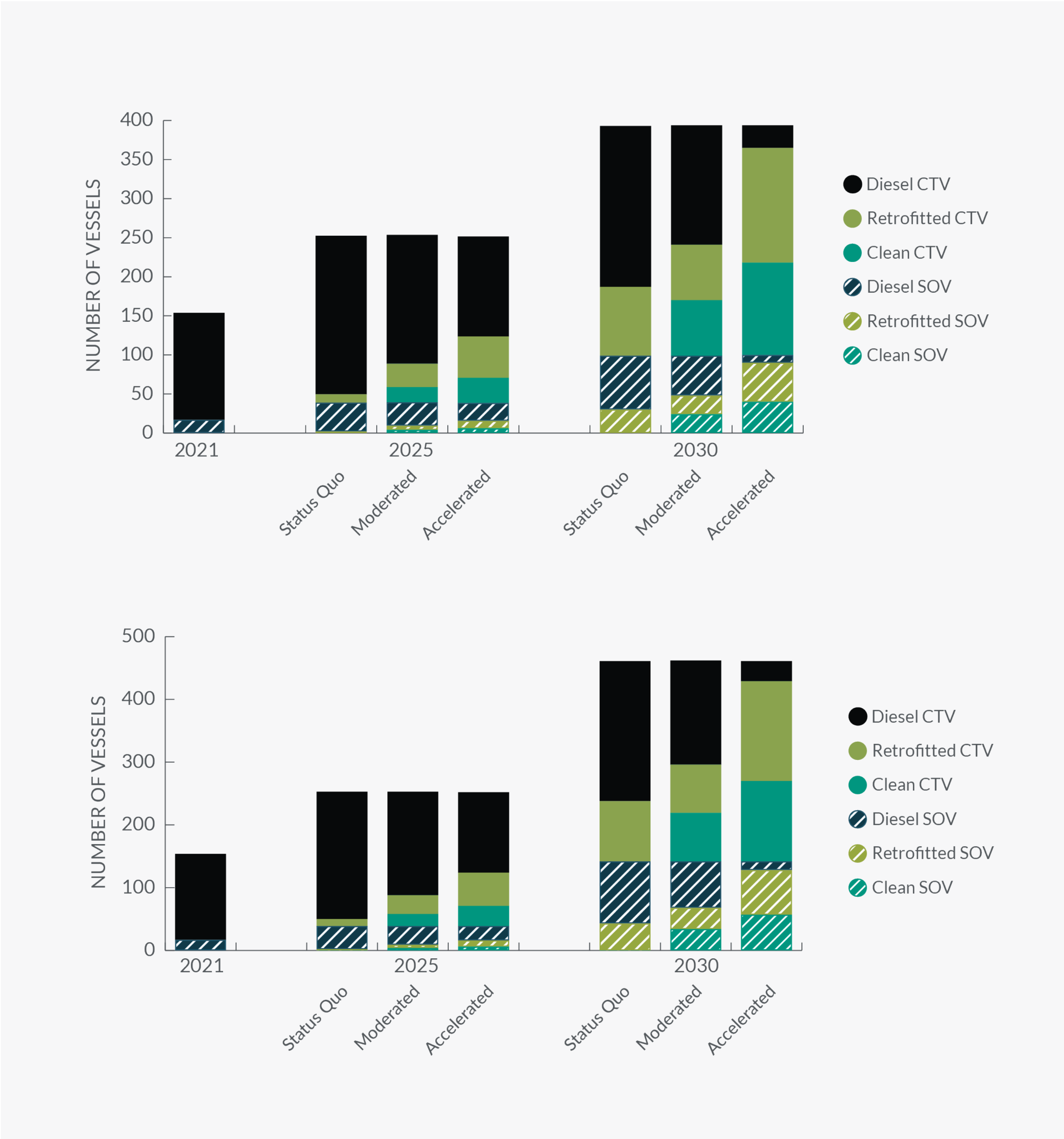


Figure 7.3: Projections on number of SOVs and CTVs broken down by fuel type for base and high case North Sea offshore wind capacity scenario.

Suggested actions are as following:

Economic barriers and corresponding actionsA

Table 7-5: Economic barrier breakdown with appropriate enabling actions.

Barrier	Enabling action	Actor (who can enable this?)
Cost differential between conventional and alternative fuels	More flexible, larger funding sources are essential for demonstrations of clean maritime technologies due to their complexity. This will be essential to bring cost parity of alternative and conventional fuels until they achieve economies of scale and encourage competitors to collaborate. **(#1)**	Governments Grant awarding bodies
Capital cost of clean maritime technologies	Encourage O&M fleet decarbonisation through public policy exemptions to balance operating cost increases (including retrofitting incentives). For instance, innovative decarbonisation measures could be supported through The Crown Estate's Leasing Rounds by offering rental discounts, or CfD auction mechanisms that encourage/mandate dedicated funding for maritime decarbonisation. **(#2)**	Agencies/ Organisations awarding Seabed Leasing/CfD or other incentive mechanisms
Cost of capital (finance)	Development of a Cost Reduction Monitoring Framework (CRMF) similar to that developed in offshore wind to set trajectories for cost reduction of offshore wind and conduct ongoing annual monitoring against plans (see Case Study below). **(#3)**	Government, Industry, Research Community, Research Technology Organisations (RTOs)
Lack of clarity over fuel pathways	Ensure that North Sea maritime decarbonisation is included in the cross-departmental Hydrogen Strategy within the UK Government. A clarity over fuel pathways is crucial for ports and vessel operators to secure investments in alternative fuel infrastructure see case study: Germany's National Hydrogen Strategy. **(#4)**	Government
Disproportionate carbon pricing	Consider pricing of fossil fuels used in maritime sector. Fiscal measures aimed at impacting the price of conventional fuels would improve the business case for clean maritime technologies. **(#5)**	Governments

Case study

German 'Sustainable Modernisation of Coastal Ships' (NaMKü) funding mechanism

€10 million per year funding provided by the Federal Ministry of Transport and digital infrastructure. The aim is to modernise coastal shipping in a sustainable and technology-agnostic manner. Innovation funding and financial incentives are intended to reduce air pollutants and greenhouse gases, as well as to improve the energy efficiency of ships.

Applicants can apply for funding for:A

- **Engine modernization**

The additional investment costs for the acquisition of a lower-emission engine compared to the costs of a conventional diesel engine including any equipment and conversion costs. This can include purely electric drives and engine modernisations, which would allow, for example the use of more sustainable fuels.

- **Measures to reduce pollutants**

The investment costs for the acquisition of systems and installation costs for exhaust secondary treatment systems, synthesis gas generators, fuel-water emulsion systems and water injection systems.

- **Measures to improve energy efficiencyA**

The acquisition of the technology and the implementation of measures that improve the energy efficiency of vessels.

Funding available to any company based in the Federal Republic of Germany under private law that owns a coastal ship. Funding can be used both for new ships and retrofits. Grant funding for up to 40% of expenditure (30% on energy efficiency measures). The scheme launched January 2021 with applications for funding beginning in February.

Case study

Germany's National Hydrogen Strategy

The Strategy's aims and ambitions:A

- Assume global responsibility in emissions reductions by establishing hydrogen as an option for decarbonisation.
- Make hydrogen competitive by pushing cost reductions with a fast international market ramp-up, which would enable technological progress and scaling effects.
- Develop a "home market" for hydrogen technologies in Germany and pave the way for imports. "The Federal Government sees a hydrogen demand of about 90 to 110 TWh until 2030. In order to cover part of this demand, generation plants with a total capacity of up to 5 GW, including the necessary offshore and onshore energy generation, are to be built in Germany by 2030… It must be ensured that the demand for electricity induced by the electrolysis plants does not result in an increase in CO_2 emissions."
- Establish hydrogen as an alternative energy carrier to enable the decarbonisation of hard-to-abate sectors.
- Make hydrogen a raw material for industry sustainability by switching current production on the basis of fossil energies to renewable energies, and pushing the decarbonisation of emission-intensive industry processes using hydrogen and its derivatives.
- Enhance the transport and distribution infrastructure by using Germany's existing gas infrastructure, but also by extending dedicated hydrogen networks or building new ones.
- Support research and train qualified personnel in order to systematically get industrial scale solutions to application maturity by 2030.
- Design and accompany transformation processes in dialogue with businesses, science, and citizens.
- Strengthen the German economy and secure global market opportunities for German companies.
- Establish international hydrogen markets and cooperation because Germany will have to import sizeable amounts of hydrogen in the medium and long term.
- Understand global cooperation as an opportunity.
- Further develop and secure quality infrastructure for hydrogen production, transport, storage and use and create confidence given the physical and chemical properties of hydrogen.
- Constantly improving framework conditions and taking up current developments.

Abridged from CLEAN ENERGY WIRE

Case Study

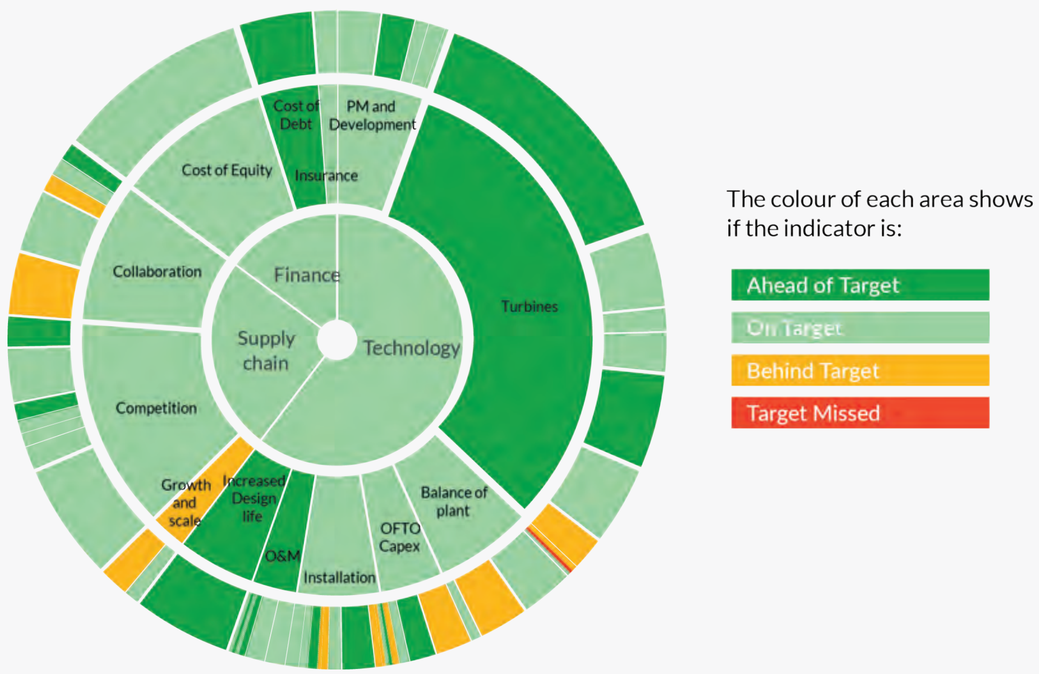
Cost Reduction Monitoring Framework'(CRMF)

In the early stages of offshore wind development the technology was expensive relative to other sources of power generation, and both government and industry were keen to demonstrate that there was a clear and credible plan for cost reduction.

The Offshore Wind Industry Council (OWIC) approved the Cost Reduction Monitoring Framework (CRMF) on 24th February 2014.

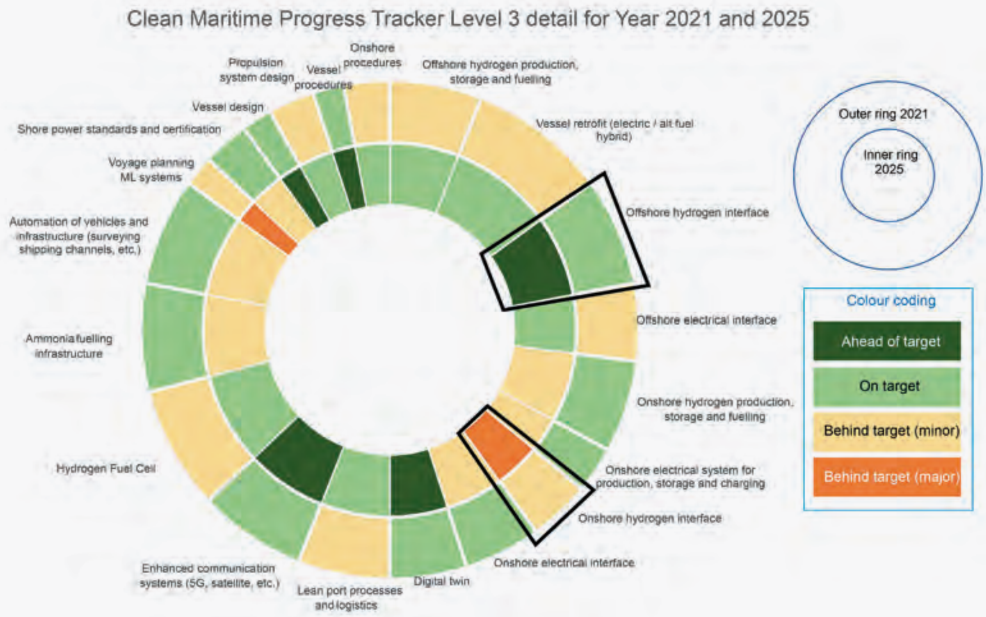
OWIC identified the need for the progress being made on cost reduction to be tracked against an agreed schedule of milestones and for an average Levelised Cost of Energy (LCoE) to be published for the most recent projects of the time. The CRMF was designed to show that Levelised Cost of Energy (LCoE) of offshore wind was capable of achieving the target of £100/MWh by 2020, set in the 2012 Crown Estate Cost Reduction Pathways report (https://www.thecrownestate.co.uk/media/1770/ei-offshore-wind-cost-reduction-pathways-study.pdf), and helped to provide a commonly recognised and accepted understanding within industry and government in terms of the direction of travel and ambitions for industrialisation and cost reduction.

The image below is taken from the 2015 CRMF report and provides a visual representation of the results. The size of the area assigned to each indicator is proportional to its contribution to the cost reduction target.



Case Study continued

The image below is an illustrative depiction of the impacts of adopting a similar method to the offshore wind's CRMF. It could benefit both policy makers and industry to develop cost reduction plans for both operating and capital costs of clean maritime technology/infrastructure.



Policy/Regulatory barriers and corresponding actionsA

Table 7-6: Policy/regulatory barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Lack of targets and deadlines	Establish a 'level playing field' and provide investor confidence by establishing short, medium and long-term maritime decarbonisation targets to demonstrate ambition and encourage organisations to make plans and investments. **(#9)**	Governments and/or Industry
	Ensure that the national infrastructure commission supports the hydrogen infrastructure needs around ports. **(#10)**	Government

Structural barriers and corresponding actionsA

Table 7-7: Structural barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Existing port infrastructure **Portside electrical power constraints**	The £70m offshore wind manufacturing investment support scheme for major portside hubs is an important step in developing an infrastructure fit for purpose. Further funding to tackle infrastructure within ports will be necessary. **(#13)**	Governments (National and Regional)

See case study on EU shore-power regulations.

Case Study

EU Shore-Side Electricity supply regulations

EU directive on the deployment of alternative fuels infrastructure sets out responsibilities for ports within the EU to supply shore side electricity.

"Member States shall ensure that the need for shore-side electricity supply for inland waterway vessels and seagoing ships in maritime and inland ports is assessed in their national policy frameworks. Such shore-side electricity supply shall be installed as a priority in ports of the TEN-T Core Network, and in other ports, by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits." [109]

"Member States shall ensure that shore-side electricity supply installations for maritime transport, deployed or renewed as from 18 November 2017, comply with [EU] technical specifications.

7.5.2 Enabling Actions to achieve the Accelerated scenario

In addition to actions listed above, the ‘medium-level’ risks will need to be addressed in order to get to the Accelerated scenario. This would allow decarbonisation of CTVs and SOVs by 40% in 2025 and by 90% in 2030 as shown in Figure 7-3 . Addressing all these risks and achieving Accelerated scenario would mean an almost complete decarbonisation of O&M fleet by 2030.

Suggested actions are as following:

Economic barriers and corresponding actionsA

Table 7-8: Economic barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Lack of knowledge of future fuel cost	More flexible, larger funding sources are essential for demonstrations of clean maritime technologies due to their complexity. This will be essential to bring cost parity of alternative and conventional fuels until they achieve economies of scale and encourage competitors to collaborate. **(#1)**	Governments Grant awarding bodies
Limited profit margins available	Encourage O&M fleet decarbonisation through public policy exemptions to balance operating cost increases (including retrofitting incentives). For instance, innovative decarbonisation measures could be supported through The Crown Estate’s Leasing Rounds by offering rental discounts, or CfD auction mechanisms that encourage/mandate dedicated funding for maritime decarbonisation. **(#2)**	Agencies/Organisations awarding Seabed Leasing/CfD or other incentive mechanisms
	Development of a Cost Reduction Monitoring Framework (CRMF) similar to that developed in offshore wind to set trajectories for cost reduction of offshore wind and conduct ongoing annual monitoring against plans. **(#3)**	Government, Industry, Research Community, Research Technology Organisations (RTOs)

Policy/Regulatory barriers and corresponding actionsA

Table 7-9: Policy/regulatory barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Safety codes for new fuels and electrical marine charging systems	Establish a programme of work that will progress and develop safety codes and standards for lower emission fuels and electrical charging systems in tandem with the R&D/Demonstration of technologies. **(#6)**	Governments, Regulators, Industry, Class Societies
Lack of standards	Engage with, and help shape, European initiatives to develop North Sea hydrogen infrastructure for OSW farms. **(#7)**	Governments, Industry, Regulators, Research Community, RTOs, Class Societies
	Guarantee a collaboration mechanism to build on existing links between UK researchers, companies and European counterparts. **(#8)**	Governments, Research community, RTOs
	To accelerate complex demonstration projects, make regulatory sandpits easy to access and multiagency; lessons should be learned from the integrated approach to innovation of the Oil and Gas Authority (OGA), the O&G regulator. **(#9)**	Governments, Regulators
Imperfect information about emissions	Develop standardised emissions data collection for O&M vessels and identify emissions baseline.**(#12)**	Governments, Industry, Research Community, RTOs, Class Societies

Structural barriers and corresponding actionsA

Table 7-10: Structural barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Split incentives	Development of an OPEX incentive for investing in clean maritime technologies. **(#14)**	Governments
Contract lengths	A common industry approach to longer charter durations for clean maritime vessels would provide greater investor confidence and support a move to investment in OSW clean maritime. **(#15)**	Industry

Organisational barriers and corresponding actionsA

Table 7-11: Organisational barrier breakdown with appropriate enabling actions.

Barrier	Action	Actor (who can enable this?)
Lack of in field performance data	Development of common data benchmarking system, similar to SPARTA in offshore wind. Using anonymised and aggregated data and providing industry benchmarking for clean maritime performance (including vessel, ports, alternative fuel and electrical charging infrastructure). **(#16)**	Governments, Industry, Research Community, RTOs
Lack of horizontal collaboration between competitors	Greater support and encouragement for Joint Industry Programmes (including aspects of R&D/Demonstration), including collaboration between government(s), regulators, class societies, industry and the supply chain on technical and non-technical work. **(#17)**	Governments, Industry, Regulators, Research Community, RTOs, Class Societies.
Lack of vertical collaboration along the supply chain		

7.6 Summary

The enabling actions set out in the Roadmap above provide recommendations for decision makers in government and industry to make interventions that can support and enable the transition to clean maritime O&M in North Sea offshore wind.

No single option is likely to provide a complete solution, and governments and industry should consider all of the options at their disposal.

Further engagement and consultation between the 'Actors' identified is recommended in order to ensure collective action toward delivery of a suite of coordinated and sustained interventions that can achieve significant impact.

The economic geography of the North Sea and of the offshore wind industry are multi-national with both UK and other European operators and supply chains reliant on the movement and interoperability of vessels, technicians and crews throughout the North Sea. Common approaches and solutions to address barriers are therefore recommended.

Some solutions to the barriers identified have been overcome to some degree in other sectors. For instance high capital costs can be overcome by innovative finance models and leasing options. Opportunities such as these could pave the way for high CAPEX costs to be incorporated as OPEX payments by companies that find the capital costs prohibitive.

Further work is recommended to maintain and continually enhance the roadmap in order for it to maintain relevance in a strategic environment that changes quickly due to advances and developments in technology, policy, regulation and socio-economics.

Whilst many of the enabling actions outlined above would likely have an indirect effect in stimulating the clean maritime supply chain, they are not recommendations aimed at direct supply chain development. Further work is recommended to explore UK Offshore Wind maritime supply chain capabilities, gaps, opportunities and stimulus measures, including opportunities and priorities for R&D, demonstration and growth programmes. Such measures should be backed by further research and linked to the priority areas for technology development and cost reduction identified by industry in this roadmap and future revisions.

Other areas for further consideration in terms of supply chain support should include measures to help the UK supply chain compete on a level playing field with European counterparts. These could include finance programmes such as domestic ship building credit guarantees, and incentive measures for vessel retrofit such as the German Federal funding mechanism (NaMKu) to support the retrofit of coastal shipping (including offshore wind service vessels) with clean maritime upgrades.

8 CONCLUSIONS

There is broad support for an accelerated transition to clean maritime operations in North Sea OSW O&M with extensive industry engagement having suggested an appetite to transition to clean maritime at an accelerated pace relative to the broader maritime sector. That said, the industry operates on a commercial basis and any transition must be not only environmentally but also commercially sustainable.

The offshore wind industry has been a major success story in Europe and in particular the North Sea, with high levels of deployment and continual cost reduction in terms of levelized cost of energy. This trend of continual cost reduction has resulted in a focus on increased optimisation, productivity and efficiency, meaning that operating models and OPEX budgets for offshore wind are extremely lean and leave little room for manoeuvre, in terms of discretionary investment in novel technology such as clean maritime where differentials in both CAPEX and OPEX are likely to prove a barrier to rapid adoption if not addressed.

It appears that much of the technology exists to deliver the vision of a decarbonised North Sea O&M fleet for offshore wind. Nevertheless, many non-technical barriers remain and will need to be addressed in order to deliver the vision and unlock the social benefits and economic opportunity presented by the accelerated transition.

No single technology or technologies could be presented as a panacea for wholescale, rapid transition. Technologies and innovation in vessel design and hull types, alternative fuel and electric drive systems, charging and fuelling infrastructure (both onshore and offshore), and digitalisation, AI and automation all having an important role to play. Meanwhile, there appears to be consensus when it comes to both the critical importance and the level of challenge involved in ensuring that ports are equipped to support the clean maritime fleet of the North Sea by providing the essential infrastructure required for alternative fuelling and electrical charging of vessels.

Under accelerated scenarios for decarbonisation, it is clear that consideration must be given to the existing fleet of vessels, with most ship yards today still designing and building conventionally-fuelled vessels that will likely operate for a minimum of 15 years. Many of these vessels will need to be retrofitted in order to achieve an accelerated transition to a decarbonised O&M fleet for the North Sea and the limited profit margins for many of these vessels means that a high cost retrofit is unlikely to be a viable investment without either some form of CAPEX support for the retrofit costs or a significant change in the differential between the operating costs of conventional and alternative propulsion fuels.

There appears to be broad acceptance of the importance of and need for clean maritime transition targets in order to set clear expectations and establish a 'level playing field' among competitors and send clear signals to investors. Whilst targets and deadlines are commonly accepted as necessary, nevertheless the industry will require complementary support and incentives to enable the supply chain to rise to the challenge and make the necessary adjustments to transition.

Whilst the economic opportunity presented by the future clean maritime industry is recognised and understood, it nevertheless requires intervention to establish the viability of and de-risk high cost and often First Of A Kind (FOAK) technologies before production reaches a scale that can drive cost reduction.

Standardisation is another important area for focus to ensure that the industry can transition to clean maritime operation in a way that is both safe, and cost effective, with vessels able to operate across the North Sea with confidence that their vessels will be interoperable regardless of which wind farm or port they visit. This will require concerted and strategic action from North Sea Governments and industry, and greater collaboration between offshore wind developers and the maritime supply chain, regulators and class societies.

The offshore wind industry is uniquely placed with the vision, expertise and ambition to act as a springboard for broader maritime decarbonisation. With support from governments and concerted action from industry, North Sea offshore wind can lead the UK, Europe and the world in developing commercially viable operating models for clean maritime and stimulating the development of standards, professional services and a thriving clean maritime industry.

Table 8-1 summarises the barriers to decarbonising maritime operations in North Sea offshore wind O&M found in this report. Linked to these barriers are enabling actions to overcome these barriers and identification of the actor(s) best placed to carry them out.

Table 8-1: Barriers and enabling actions.

<table>
<tr><th>Barrier</th><th>Enabling action</th><th>Actor (who can enable this?)</th></tr>
<tr><td>Cost differential between conventional and alternative fuels</td><td rowspan="5">1. More flexible, larger funding sources are essential for demonstrations of clean maritime technologies due to their complexity. This will be essential to bring cost parity of alternative and conventional fuels until they achieve economies of scale and encourage competitors to collaborate.

2. Encourage O&M fleet decarbonisation through public policy exemptions to balance operating cost increases (including retrofitting incentives). For instance, innovative decarbonisation measures could be supported through The Crown Estate's Leasing Rounds by offering rental discounts, or CfD auction mechanisms that encourage/mandate dedicated funding for maritime decarbonisation.

3. Development of a Cost Reduction Monitoring Framework (CRMF) similar to that developed in offshore wind to set trajectories for cost reduction of offshore wind and conduct ongoing annual monitoring against plans.</td><td rowspan="5">Governments

Grant awarding bodies

Agencies/Organisations awarding Seabed Leasing/CfD or other incentive mechanisms

Government, Industry, Research Community, RTOs</td></tr>
<tr><td>Capital cost of clean maritime technologies</td></tr>
<tr><td>Cost of capital (finance)</td></tr>
<tr><td>Lack of knowledge of future fuel cost</td></tr>
<tr><td>Limited profit margins available</td></tr>
<tr><td>Lack of clarity over fuel pathways</td><td>4. Ensure that North Sea maritime decarbonisation is included in the cross-departmental Hydrogen Strategy within the UK Government. A clarity over fuel pathways is crucial for ports and vessel operators to secure investments in alternative fuel infrastructure see case study: Germany's National Hydrogen Strategy.</td><td>Government</td></tr>
</table>

Barrier	Enabling action	Actor (who can enable this?)
Disproportionate carbon pricing	**5**. Consider pricing of fossil fuels used in maritime sector. Fiscal measures aimed at impacting the price of conventional fuels would improve the business case for clean maritime technologies.	Governments
Safety codes for new fuels and electrical marine charging systems	**6.** Establish a programme of work that will progress and develop safety codes and standards for lower emission fuels and electrical charging systems in tandem with the R&D/Demonstration of technologies.	Governments, Regulators, Industry, Class Societies
Lack of standards	**7.** Engage with, and help shape, European initiatives to develop North Sea hydrogen infrastructure for OSW farms. **8.** Guarantee a collaboration mechanism to build on existing links between UK researchers, companies and European counterparts. **9.** To accelerate complex demonstration projects, make regulatory sandpits easy to access and multiagency; lessons should be learned from the integrated approach to innovation of the Oil and Gas Authority (OGA), the O&G regulator.	Governments, Industry, Regulators, Research Community, RTOs, Class Societies Governments, Research community, RTOs Governments, Regulators
Lack of targets and deadlines	**10.** Establish a 'level playing field' and provide investor confidence by establishing short, medium- and long-term maritime decarbonisation targets to demonstrate ambition and encourage organisations to make plans and investments. **11.** Ensure that the national infrastructure commission supports the hydrogen infrastructure needs around ports.	Governments and/or Industry Government
Imperfect information about emissions	**12.** Develop standardised emissions data collection for O&M vessels and identify emissions baseline.	Governments, Industry, Research Community, RTOs, Class Societies
Existing port infrastructure **Portside electrical power constraints**	**13.** The £70m offshore wind manufacturing investment support scheme for major portside hubs is an important step in developing an infrastructure fit for purpose. Further funding to tackle infrastructure within ports will be necessary.	Governments (National and Regional)
Split incentives	**14.** Development of an OPEX incentive for investing in clean maritime technologies.	Governments
Contract lengths	**15.** A common industry approach to longer charter durations for clean maritime vessels would provide greater investor confidence and support a move to investment in OSW clean maritime.	Industry
Lack of in field performance data	**16.** Development of common data benchmarking system, similar to SPARTA in offshore wind. Using anonymised and aggregated data and providing industry benchmarking for clean maritime performance (including vessel, ports, alternative fuel and electrical charging infrastructure).	Governments, Industry, Research Community, RTOs
Lack of horizontal collaboration between competitors **Lack of vertical collaboration along the supply chain**	**17.** Greater support and encouragement for Joint Industry Programmes (including aspects of R&D/Demonstration), including collaboration between government(s), regulators, class societies, industry and the supply chain on technical and non-technical work.	Governments, Industry, Regulators, Research Community, RTOs, Class Societies.

9 ACRONYMS AND GLOSSARY

AEL	Alkaline Electrolysis
AHV	Anchor Handling Vessel
AI	Artificial Intelligence
BEIS	UK Government Department for Business, Energy and Industrial Strategy
Carbon (Emissions):	See CO_2e emissions
CCS	Carbon Capture and storage
CfD	Contract for Difference
CMP	Clean Maritime Plan. A UK Government (Department for Transport) document setting out a national action plan to take UK maritime towards a vision for zero emissions shipping
CO_2 emissions	Carbon dioxide emissions
CO_2e emissions	Emissions of the three greenhouse gases (Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O)) weighted according to their global warming potential
CPP	Controllable Pitch Propeller
CTV	Crew Transfer Vessel. A vessel used to transfer crew between the shore and the windfarm
Daughter craft	Smaller vessels designed to operate from a larger vessel
DEF	Diesel Exhaust Fluid
DNO(s)	Distribution Network Operators. Companies that own and operate the infrastructure used to distribute electricity around the UK.
DP	Dynamic Positioning
DfT	UK Government Department for Transport
EGR	Exhaust Gas Recirculation
FCDO	Foreign, Commonwealth & Development Office
FFP	Forward Facing Propellers
FPP	Fixed Pitch Propeller
GHG Emissions	Emissions of the three major GreenHouse Gases: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O)
Green Hydrogen	Hydrogen produced using electricity from renewable sources
Greener	A term used to identify practices and technologies with a lower environmental impact. In the context of this piece, usually referring to lower carbon emissions but also local pollutants
GWP	Global Warming Potential
H&S	Health and Safety
Hs	Significant wave height. The mean height of the highest third of waves passing a point
IMO	the International Maritime Organization
LCOE	Levelised Cost of Electricity. A metric used to determine the average cost of energy produced by a wind farm over it's lifetime or contract

$LiCoO_2$	Lithium Cobalt Oxide
LiFePO4	Lithium Iron Phosphate
LiMn2O4	Lithium Manganese Oxide
$LiNiMnCoO_2$	Lithium Nickel Manganese Cobalt Oxide
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MoD	Ministry of Defence
MSR	Molten Salt Reactor
NO_x	Nitrogen Oxides. A group of pollutants released when burning fuels. They have an effect both on local air quality and global warming.
O&G	Oil and Gas
O&M	Operations and maintenance
OSV	Offshore Service Vessel
OSW	Offshore Wind
PAX	Passengers. Refers to how many passengers a vessel carries
PEM	Proton Exchange Membrane Electrolysis
POB	Person on Board
PWR	Pressure Water Reactor
	R&D Research and Development
RIB	Rigid Inflatable Boat
ROV	Remotely Operated Vehicle
SOV	Service Operation Vessel. A large vessel designed to be a platform for wind farm support, housing personnel and equipment. Usually deployed in wind farms further from the shore
SCR	Selective Catalyst Reduction
SES	Surface Effect Ship
SOEC	Solid Oxide Electrolysis Cell
SOV	Service Operations Vessels
SO_x	Sulphur Oxides. A group of pollutants that are released when burning some marine fuels containing Sulphur. They have a detrimental effect on local air quality.
SWATH	Small-Waterplane Area Twin Hull
TRL	Technology Readiness Level – A scale designed to show how mature a technology is. From 1-9 with 1 representing very early research and 9 being already deployed and operational
WDV	Wind Farm Development Vessel
W2W	Walk to Work
WTIV	Wind Turbine Installation Vessel
VSP	Voith Schneider Propeller
ZES	Zero Emission Services

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APPENDIX 1 – MODEL BUILDING AND REVIEW QUALITY ASSURANCE

Table A1-1: Model building and review quality assurance.

No.	Model component	Process	Comment
1	Model Control Environment	Access, change and version control	Models are saved in a project-specific designed folder in Microsoft Teams accessible by the project team only. No read only or password protected versions were considered necessary. Changes to the market growth model were made by the immediate team of analysts only, who are delegated for the delivery of this task. New model versions were identified by a numbering suffix on file names and communicated between the team to avoid confusion.
2		Back-Up and Recovery	Files are saved as new versions and past versions are kept if fundamental changes are made to the structure of the model, so it is easier to go back to previous steps of development. This made comparing formulas and tracking errors easier, as well as allowing analysts to revisit previous decisions. Our corporate system uses the OneDrive cloud system for storage which allows full recovery of files in cases of disruption or accidental deletion.
3		Single person dependency	The model task was assigned to a team of two project members (Senior Strategy Analyst and A&I Manager) from our organisation with supervision by the Team leader where necessary. The model structure and basic assumptions on vessel usage was developed initially by a single person but addition of necessary elements for future growth scenarios, fuel prices and vessel emissions conducted from both members of the team. Members were keeping constant communication from the beginning challenging results constantly to identify errors. Files were saved on accessible folders, so no risk of single person dependency existed. Workshops were organised with key vessel industry stakeholders to present preliminary results and receive independent feedback on assumptions and results.
4		User Guide and Succession Planning	The model is structured following a common format adopted for all models we develop in the wider team, so this allows easy handover to any other member. No user guide was considered necessary for this level of model complexity. The report drafting for this work gives all the details necessary to understand the methodology, background of the model approach and interpretation of the results. Where inputs or other elements are hard coded, a note is added in relevant cells to explain and reference the sources from where this data came. This provides a proactive approach to any key questions may arise from a new user and considers contingency scenarios where immediate users are absent and another user needs to quickly gain an understanding of the model.
5		Documentation Standards	Market and cost models are developed within the A&I team following a generic format agreed for building in-house models and using functional elements from the FAST modelling standard. Templates from previous projects are used, including different colours for hardcoded inputs, dependent variables, results and parts needing verification. As a general policy it is up to the analyst to develop a clean model adding any clear instructions and data sources necessary to help a new user to obtain full functionality.
6		Skills and Experience	The actual model was developed in excel using basic formulas so no specialised capability is needed to understand its functionality and the development process. To facilitate the process of obtaining the relevant windfarm capacity data from detailed external databases, the Excel add-in of Power Query was used to list the different scenario combinations. Model developers know how the data from different sources modified and formed the inputs in the final model.

No.	Model component	Process	Comment
7	Model Accuracy and Reliability	Developed in line with model life-cycle	Details on the purpose of the model were specified by the Project Manager and the client during the development of the scope. Regular meetings (bi-weekly) and direct conversations between the team and the policy customer were needed from development to delivery of the model were conducted to discuss requirements, timelines, obstacles, and support that might be needed in any part of the project. During model building any comments and changes were promptly communicated from PM and delivery team either through calls, emails or other Teams features to provide transparency, avoid overlaps and eliminate delays. The outputs of the model were shared with the customer in first draft and with stakeholders during workshops to ensure that they adequately answer the question set.
8		Input Validation	Inputs of the model and their sources are presented in "Vessel and Wind Farm Growth Scenarios" section and in Appendix 2. Inputs were taken from literature, previous closed projects, our in-house analysis, and expert engineering knowledge and validated where possible receiving feedback from key stakeholders in terms of accuracy and reliability. Fuel price forecast are based on BEIS crude oil prices official statistics 2019 so newer releases can affect price trajectories and estimations on fuel cost. For this analysis, the 2020 prices are provisional based on the central scenario projected.
9		Developer Testing	Model is tested constantly for errors from developers and team leader by conducting verification checks on formulas and observing abnormalities in outputs through plotted charts.
10		Communication of Model Limitations and Uncertainty	Due to the nature of the forecast referring to new technologies still in initial stage of adaptation, the long-term scope by 2030 and the wider international market and policy complexities associated with decarbonisation of vessels, a number of simplified assumptions should have to be made. Limits of the model have been outlined in the report in the Methodology and Quality assurance section. The main variables which introduce uncertainty are about the SOVs/CTVs strategies for O&M activities in correlation with windfarm size, the level of clean technologies' adaptation and the fuel price projections. For the fuel prices as described in point 8, forecasts are updated annually and might affect the results in terms of cost and implied carbon price. Inputs affecting the outputs are grouped together separately in Assumptions tab and scenarios can be selected from dropdown lists so sensitivities on individual and group of assumptions can be easily tracked to understand their impact in the final results.
11		Independent Review	The Head of Analysis & Insights conducted internal reviews of the model following the resourcing plan, and signed off.
12	Governance and Transparency	Governance	Project Manager and delegated team coordinated the process of monitoring progress, raise issues, set timescales, highlight urgent requests to relevant teams, challenge outputs, ask for clarifications and represent the team to DfT but ask for further information or representation from modelling team if model details required.
13		Transparency	Model outputs have been published in the final report where key inputs and sources are presented to help the reader understand better the approach followed.

APPENDIX 2 – O&M VESSELS MODEL ASSUMPTIONS

Table A2-1: Transit time projections of O&M vessels in offshore wind for North Sea countries.

Assumption	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Distance to shore	km	49.90	52.30	54.70	57.10	59.50	61.90	64.30	66.70	69.10	71.50	73.90
Transit time port - site												
SOV	h	3.85	4.03	4.22	4.40	4.59	4.77	4.96	5.15	5.33	5.52	5.70
CTV	h	2.69	2.82	2.95	3.08	3.21	3.34	3.47	3.60	3.73	3.86	3.99
Transit time per turbine repair												
SOV	h	0.96	1.01	1.05	1.10	1.15	1.19	1.24	1.29	1.33	1.38	1.43
CTV	h	0.67	0.71	0.74	0.77	0.80	0.84	0.87	0.90	0.93	0.97	1.00
Annual transit time per turbine repair												
Minor repair												
SOV	h	19.25	20.17	21.10	22.02	22.95	23.87	24.80	25.73	26.65	27.58	28.50
CTV	h	13.47	14.12	14.77	15.42	16.06	16.71	17.36	18.01	18.66	19.30	19.95
Preventative maintenance												
SOV	h	0.96	1.01	1.05	1.10	1.15	1.19	1.24	1.29	1.33	1.38	1.43
CTV	h	0.67	0.71	0.74	0.77	0.80	0.84	0.87	0.90	0.93	0.97	1.00
Annual transit time per turbine												
SOV	h	20.21	21.18	22.15	23.12	24.10	25.07	26.04	27.01	27.98	28.96	29.93
CTV	h	14.15	14.83	15.51	16.19	16.87	17.55	18.23	18.91	19.59	20.27	20.95

Table A2-2: Fuel energy density and price assumptions.

Metric	Unit	MGO	H_2
Energy conversion factor	MJ/kWh	0.2778	
Specific energy	MJ/kg	41	120
Specific energy	kWh/kg	11.39	33.34
Conversion factor	L/t	1,1183	9,000
Conversion factor	L/MWh	103.9	29.9

Table A2-3: Fuel cost assumptions based on 3 different growth scenarios.

	Brent price ($/bbl)		H_2 ($/kg)	
Year	2019r	2030	2019r	2030
Fuel price (Low)	60	49	2.50	1.20
Fuel price (Central)	63	79	3.50	1.98
Fuel price (High)	65	118	4.50	2.75

Note: a 15% premium was added to Brent to adjust forecasts for MGO. MGO conversion factor 159 litres per barrel. FOREX GBP to USD was assumed 0.75. Fuel prices were converted to £ per kg and then to £ per MWh.

Sources:A

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APPENDIX 3 – EMISSION CALCULATIONS

The following assumptions were used in fuel and emission calculations for CTV and SOV examples provided in the report.

Table A3-1: Assumptions for fuel and emissions calculations.

	CTV		SOV	
Input	Distance to wind farm (km)	40	Distance to wind farm (km)	100
	Speed (km/h)	40	Speed (km/h)	20
	Fuel consumption - transit (l/h)	320	Fuel consumption - transit (l/hr)	1,000
	Fuel consumption - idling (l/h)	52	Fuel consumption - Infield (l/hr)	120
	Idling time per trip (h)	8	Shift length (weeks)	2
	Number of trips per year (-)	200	Distance traveled for shift change (km)	100
	Fuel price (£/l)	0.4	Stock replenishment in port (weeks)	4
	Number of technicians (-)	12	Charter length (weeks)	16
			Fuel price (£/l)	0.4
Results	Fuel used in a year (l)	211,200	Fuel used per charter (l)	378,960
	Cost of fuel (£)	84,480	Cost of fuel (£)	151,584
	Number of transfers per year (-)	4,800	Fuel used per year (l)	378,960.00
			Cost of fuel per year(£)	151,584.00

The calculated fuel consumptions were translated into emissions using government published fuel conversion factors [19].

Table A3-2: Fuel consumption to emissions conversion using government published factors.

Fuel	Unit	kg CO_2e	kg CO_2	kg CH_4	kg N_2O
Marine gas oil	tonnes	3,249.99	3,205.99	0.81	43.20
	litres	2.77540	2.73782	0.00069	0.03689
	kWh (Net CV)	0.27485	0.27113	0.00007	0.00365
	kWh (Gross CV)	0.25836	0.25486	0.00006	0.00343
CTV Annual Fuel Usage (l)	211,200	586,164.5	578,227.6	145.7	7,791.2
SOV Annual Fuel Usage (l)	378,960	1,051,765.6	1,037,524.3	261.5	13,979.8

APPENDIX 4 – TECHNOLOGY READINESS LEVEL SCALE

Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. TRL are based on a scale from 1 to 9 with 9 being the most mature technology. The use of TRLs enables consistent, uniform discussions of technical maturity across different types of technology. TRLs, by themselves, may not always relate clearly to risk, cost and schedule. For instance, some technology at a low TRL can mature more quickly than another at a high TRL. Please find below detailed explanation of each TRL level:

Table A4-1: Technology readiness level breakdown with a criteria description.

Level	Explanation
TRL 1	Basic principles observed. Scientific research begins translation to applied R&D: Lowest level of technology readiness. Examples might include paper studies of a technology's basic properties.
TRL 2	Technology concept formulated. Invention begins: Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
TRL 3	Experimental proof of concept. Active R&D is initiated: This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4	Technology validated in lab. Basic technological components are integrated: Basic technological components are integrated to establish that the pieces will work together.
TRL 5	Technology validated in relevant environment. Fidelity of breadboard technology improves significantly: The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
TRL 6	Technology demonstrated in relevant environment. Model/prototype is tested in relevant environment: Represents a major step up in a technology's demonstrated readiness, which is well beyond that of TRL 5. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
TRL 7	System prototype demonstration in operational environment. Prototype near or at planned operational system: Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment.
TRL 8	System complete and qualified. Technology is proven to work: Actual technology completed and qualified through test and demonstration.
TRL 9	Actual system proven in operational environment. Actual application of technology is in its final form: Technology proven through successful operations. Includes competitive manufacturing in the case of key enabling technologies.

APPENDIX 5 – ENGAGEMENT REPORT

1 Executive Summary

The report aims to explain the approach that has been taken to engaging stakeholders in the development of an innovation roadmap for the decarbonisation of O&M vessels operating in the offshore wind industry in the North Sea ('The Roadmap').

The report explains the approach taken in engaging industry stakeholders, and the ways in which ORE Catapult and the Workboat Association have had regard to the insight shared with us as we have jointly conducted this work. The engagement report also explains the way in which the insight has informed the final report to the UK Government Department for Transport (DfT) and the Foreign, Commonwealth & Development Office (FCDO).

The ORE Catapult and the Workboat Association have undertaken both extensive desk-based engineering research and market modelling with the results of industry engagement to inform the results of the Roadmap.

Industry engagement has included:

- North Sea industry engagement event. Engagement with industry stakeholders from across the North Sea region, including the UK, Belgium, the Netherland, Germany, Denmark and Sweden.
- 27 detailed Industry stakeholder interviews, each of around 1h 15m duration.
- 5 Industry workshops, involving more than 50 organisations to present, test and update draft findings.

Engagement has involved a broad range of stakeholder types, providing a representative sample from across the offshore wind industry's maritime operations function, including:

- Owners and operators of offshore wind farms
- Vessel design/build companies
- Propulsion system design and build companies
- Electrical charging and alternative fuelling system design/build and service companies
- Class societies
- Turbine OEM
- Vessel owner operators
- Port owner/operators (OO's)
- Consultants
- Alternative fuel production, distribution, storage and supply companies
- Offshore wind service providers
- Academia

The interview results have been analysed through thematic and numerical methods, ensuring thorough evaluation and reliable conclusions. The main findings from the industry interviews can be summarised by the following:

- **Section 1:** Section 1 was concerned with the collection of organisation and interviewee details.
- **Section 2:** It was common that port owner/operators are gradually receiving requests to make infrastructure upgrades to support clean maritime, however there is significant concern regarding the following: risk of investment, technology uncertainty and the lack of regulation in place.
- **Section 3:** Maritime energy system developers appear to have a considerable amount of active requests for clean maritime infrastructure, however there is significant concern regarding the following: risk of investment, logistical issues (alternate fuel supply/storage/ distribution and land constraints) and the lack of regulation in place.
- **Section 4:** Vessel designers and builders are experiencing lots of requests for clean maritime vessels, however there is a significant concern regarding the following: risk of investment, client uncertainty (operational performance and supportive infrastructure) and the lack of regulation.
- **Section 5:** Vessel operators and clients suggested that the barriers to vessel investment consisted of the following: risk of investment, lack of standardised infrastructure, short charter contracts and technology uncertainty. There was frequent reference to the chicken and egg analogy where vessel manufacturers do not want to invest in clean maritime vessels without supporting infrastructure and system developers don't want to invest in supporting infrastructure until there is an appropriate demand.
- **Section 6:** Academics, consultants, clusters and trade groups highlighted a wide array of current and previous projects/research to support clean maritime. The work mainly focussed on alternate fuel/power, onshore/offshore electrification and data benchmarking (emissions, fuel consumption and operational performance). Regarding the barriers to clean maritime, interviewees stated the barriers were: risk of investment, technology uncertainty and logistical issues. Enabling actions identified by the participants consisted of the following: industry wide collaboration, portside infrastructure investment and increased charter contracts.
- **Key enabling Technology:** All interviewees were questioned on their thoughts and opinions of the key enabling technologies to drive a rapid transition to clean maritime. The summarised technologies consisted of the following: improved battery density, port electrification and port facilities for alternate fuel bunkering.
- **Key enabling policy/regulation:** All interviewees were questioned on their thoughts and opinions of the key enabling policy and regulation to drive a rapid transition to clean maritime. The emphasised policies and regulation consisted of the following: government targets and deadlines, OPEX incentives and capital grants (alternate fuel and port infrastructure)
- **Key enabling actions from industry:** All interviewees were questioned on their thoughts and opinions of the key enabling actions required of industry to drive a rapid transition to clean maritime. The emphasised actions consisted of the following: increased collaboration throughout the supply chain and across different sectors and longer contracts for vessel tenders.

2 Introduction

ORE Catapult is the UK's leading technology innovation and research centre for offshore renewable energy. The Catapult works with government, industry, academia and the supply chain to de-risk technology, encourage growth and development throughout the UK and reduce the levelised cost of energy (LCoE).

Engaging organisations is critical to provide an industry overview and identify major regulatory, technological and market risks for the decarbonisation of the sector. Industry and stakeholder insight was gathered to understand the issues faced throughout the supply chain, their specialist and well informed opinions enable reliable conclusions that will be relayed to policy makers. To collect this data ORE Catapult launched a quad phase process to set direction, gather opinion trends, review the draft findings and identify supply chain potential.

2.1 Phase 1: Stakeholder Focus Group EventA

The initial phase of the stakeholder engagement process was an industry engagement event held 'virtually' in partnership with the UK's Department for International Trade (DiT) team in the Netherlands. The objective of the event was to inform the direction of the review and develop a preliminary understanding of industries opinions and thoughts. Engaging with industry representatives was a vital step to launch the report as it highlighted key concepts to investigate.

The event was attended by over 58 industry experts from a range organisations and industries from across the North Sea economic geography. Attendees were assigned into breakout groups to discuss, the barriers to offshore wind maritime decarbonisation, enabling actions and measures to encourage greater industry collaboration in the North Sea. After the discussions, an industry panel convened to describe their group conversations in 5 minute presentations in conjunction with a poll asking the likelihood of achieving net zero emissions, for offshore wind O&M, by 2030. The session ran for over an hour and the industry representatives were very interactive and forthcoming with their opinions.

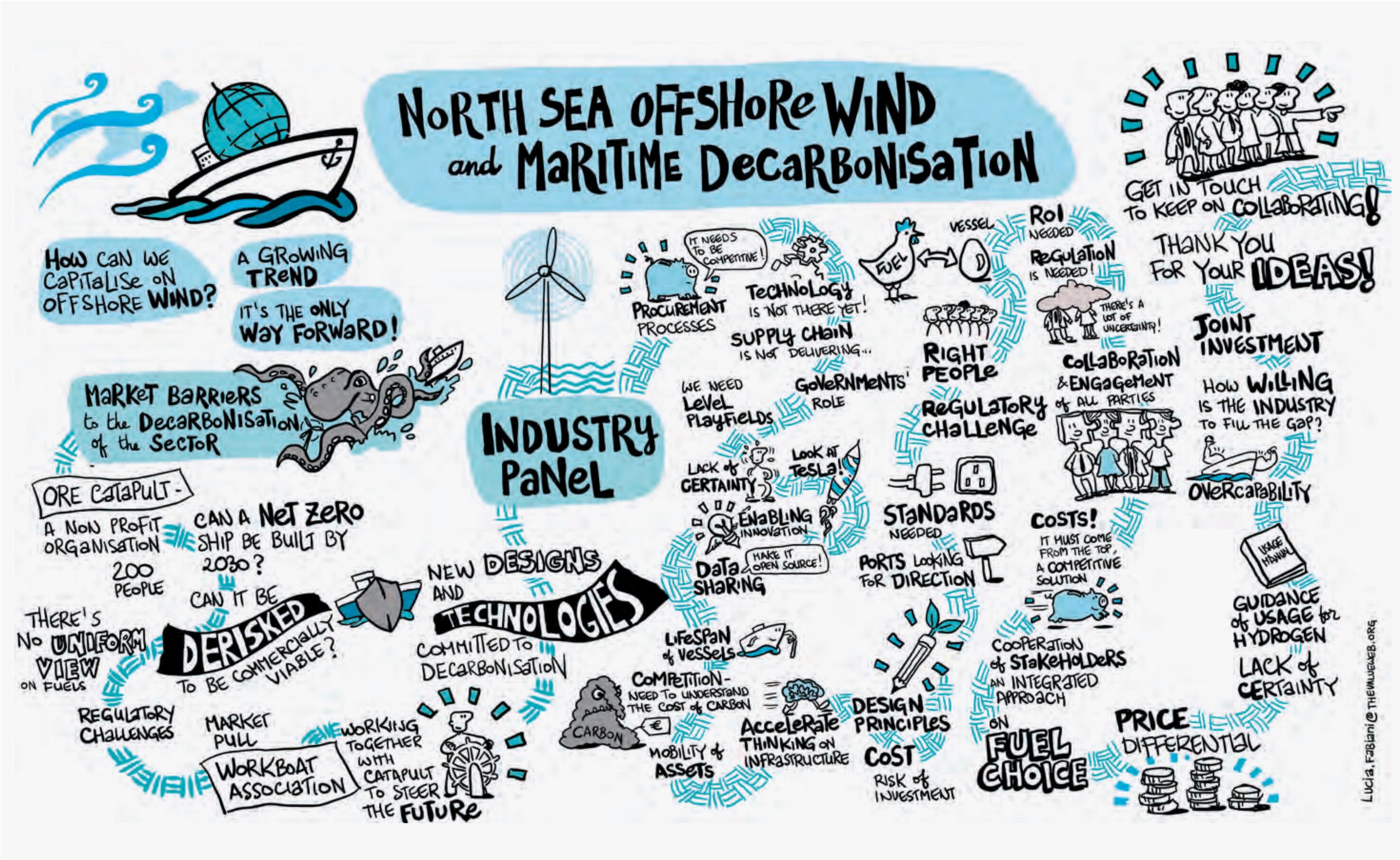

Figure A5-1: A graphic illustration produced from the event, reflecting a summary of key points discussed by attendees.

3 Phase 2: Stakeholder InterviewsA

The second part of engaging with industry was conducted via virtual stakeholder interviews. The aim of the interviews were to identify key barriers faced by industry along with potential enabling technologies and actions that could be taken to address these difficulties. Stakeholder interviews facilitated in-depth, detailed conversions that enabled specific and unique conclusions to be produced.

ORE Catapult interviewed 27 different organisations from a diverse range of business areas, organisation size and location of operations. The collective process consisted of a series of one to one interviews lasting approximately 1 hour and 15 minutes. The interviews covered 8 key topics. Section 1 asked questions about the nature of the organisation the interviewee was from as well as their roll within it. Sections 2-6 consisted of questions targeted at 5 different groups of stakeholders: Port owner/operators, maritime energy infrastructure system developers/owner/operators, vessel designers/builders, vessel operators/clients and consultants, academia, clusters and trade groups. Sections 7-8 consisted of questions targeted at all respondents and sought after numerically rated answers investigating enabling actions regarding technology, policy/regulation and industry action. The collected data was analysed thematically and numerically to derive conclusions and identify trends. Table 1 shows the organisations interviewed and their respective head office locations and leading business area. The information here is self reported by interviewees and so the 'Head Office' or 'Main business activity' reported refers in some cases to the business unit that interviewees were representing rather than the corporate organisation 'Head Office' or 'Main business activity'.

Table A5-2: Interviewee list with respective head office and main active business area.

Organisation	Head Office	Main business activity
Associated British Ports	London, GB	Port OO
Chartwell Marine	Southampton, GB	Vessel Designer
Bibby Marine Services	Liverpool, GB	Vessel Operator
Fugro	Leidschendam, NL	Vessel Operator
Louis Dreyfus Armateurs	Paris, GB	Vessel Operator
MJR Power And Automation	Stockton-on-Tees, GB	System Design/Manufacture
Northstar Renewables	Aberdeen, GB	Vessel Operator
Ørsted	Gentofte, DK	Offshore Wind OO
Siemens Gamesa Renewable Energy	Newcastle, GB	Offshore Wind SP
Tidal Transit	Egmere, GB	Vessel Operator
Windcat	Lowestoft, GB	Vessel Designer/Operator
University College London	London, GB	Academia
Lloyds Register	London, GB	Class society
Amsterdam Ijmuiden Offshore Ports	Amsterdam, NL	Port OO
Njord Offshore	Tendering, GB	Vessel Operator

The University Of Manchester, Tyndall Centre	Manchester, GB	Academia
REBO, Port of Oostende	Oostende, BE	Port OO
International Marine Contractors Association	London, GB	Industry Trade Group
Port Of Tyne	Newcastle, GB	Port OO
GE Power Conversion	Rugby, GB	Vessel Design
Carbon Trust	London, GB	Consultancy/Industry Programme (OWA)
Vattenfall	Stockholm, SE	Offshore Wind OO
Scottish Power Renewables	Glasgow, GB	Offshore Wind OO
Geos Group	Henley on Thames, GB	Energy Infrastructure
Damen	Gorinchem, NL	Shipyard
Infrastrata	London, GB	Energy Infrastructure
Yara Marine	Oslo, NO	Energy Infrastructure

Collectively, the stakeholders interviewed by ORE Catapult on behalf of the Department for Transport and the Foreign, Commonwealth & Development Office represent a significant proportion of operations in their respective sectors of the offshore wind industry, including offshore wind farm owner operators, port operators and vessel operators.

Ørsted, Vattenfall, Siemens and Scottish Power own 25 offshore wind farms in the North Sea, amounting to a total capacity of 9632 MW which accounts for over 50% of the total North Sea output [106]

The port owner/operators interviewed also represent a major industry force. Combined, Associated British Ports, Port of Tyne, Amsterdam Ijmuiden Offshore Ports and Port of Oostende (REBO) currently cover the operations and maintenance on 23 fully commissioned offshore wind farms in the North sea [106]

Looking to the future, the mentioned port OO's are looking to service a further 6 wind farms that are currently under construction, putting the collective capacity of the 29 wind farms at 12,872 MW, accounting for 44% of the total North Sea output (Fully commissioned and under/pre construction) [106].

Bibby Marine, Fugro, Northstar, Tidal Transit, Windcat, Njord Offshore and Louis Dreyfus Armateurs were the vessel operators interviewed and represent a considerable proportion of the sector. Combined, the vessel operators manage operations and maintenance on over 25 fully commissioned wind farms amounting to over 47% (8991 MW) of the total offshore wind output from the North Sea [107].

4 Phase 3: Industry WorkshopsA

After over 30 hours of interviews and draft findings concluded, it was essential to review, validate and modify the preliminary conclusions. The aim of the industry workshops was to present the draft findings to industry stakeholders and receive feedback for report modifications.

ORE Catapult and the Work Boat Association held 5 virtual industry workshops with 50 organisations present. Each workshops progressed over a 90 minute period and discussed 4 key aspects of the report: Clean maritime scenarios and market model, current and future technologies, barriers to adoption and enabling actions. The workshops operated in the format of, presentations, delivered by ORE catapult industry experts, followed by questions, polls and open discussion specific to each key report aspect. There was opportunity for stakeholders to express their opinion and the participants were very interactive and forthcoming with their thoughts and insight.

To enhance the value of feedback and enable industry opinion trends to be determined, the 5 sessions were divided into the following individual business areas:

- Vessel Design and Build
- Alternative Fuel Production and Distribution
- Electrification, Charging Systems and Batteries
- Offshore Logistics, Operational Performance and Enabling Infrastructure
- Port Logistics and Enabling Infrastructure

5 Phase 4: Stakeholder Supply Chain AssessmentA

The final phase of the stakeholder engagement process was to highlight gaps in the supply chain, assess potential UK contribution and identify actions to stimulate growth and development. Industry, government and trade bodies contacted were able to provide expert opinion and vital information for the supply chain assessment.

ORE Catapult engaged with trade representatives by hosting round table discussions and distributing supply chain templates which canvassed views of trade associations, Local Enterprise Partnerships (LEPs), Regional cluster organisations in both the offshore wind and maritime sectors, and representatives of several government departments with a role in maritime/industrial policy.

The questionnaire consisted sought information from industry experts as to the current market leaders as well as UK supply chain capability (both current and potential) in several current and emerging maritime technology areas. The established and innovative technologies assessed included:

- CTV's (Monohull, Catamaran, Trimaran, SWATH and Tri SWATH)
- Surface Effect Ships
- Rigid Inflatable Boats
- CTV Propulsions Systems (Water jet, fixed pitch, forward facing and controllable pitch)
- Diesel Engines
- SOV Propulsion Systems (Azimuth thrusters, manoeuvring thrusters and Voith Schneider propellers)
- Hydrogen Production Techniques (Electrolysis, Steam Methane Reforming with Carbon Capture, Utilisation and Storage)
- Hydrogen Combustion Engines
- Alternate Fuels (Hydrogen, ammonia, LNG, HVO, methanol, biodiesel and electrification)
- Alternate Fuels Production Techniques
- On Board Battery Technology
- Air Lubricants
- Selective Catalytic Reduction and Exhaust Gas Recirculation
- Wind Propulsion
- Shore Powering
- Hydrogen Storage (Liquid, Gaseous and Metal Halides)
- Fuel Bunkering (Onshore and Offshore Infrastructure)
- Batteries

6 Phase 1: Industry Engagement Event ResultsA

To support industry and advise government, analysis of the stakeholder focus groups is of paramount importance. Opinion trends and key barriers have been identified to inform the report and set initial direction.

After being given an introduction to the project, attendees were invited to form small groups to discuss two questions. Questions are given below along with a selection of some of the comments made.

1.AWhat are the biggest barriers to decarbonisation of offshore wind maritime logistics?A

- More radical fuel change will need more buy in from public, perception from public and perception of dangers.
- Currently no buy-in from fuel supply chain.
- Short charter lengths are deterring investment.

- Lack of certainty and lack of level playing field.
- Economics, someone needs to pay for this and will need an additional pull factor, maybe signalling from government.
- Lifespan of vessels and how can they be future-proofed.
- To achieve net zero we don't have refuelling facilities and infrastructure widely available.
- We need to understand the cost of carbon.
- Mobility of assets, if we invest in H_2 ship can we operate in all markets?
- Cost of investment in low carbon technology is not reflected in charter fee.
- We need interoperability.
- We need fuel provision and demand. It's not clear which fuel will come out on top. If it's multiple fuels this could raise issues such as space constraints.
- Fuel costs. Biofuel adaptation to CTVs would lead to significant emissions reduction, however MGO is currently cheaper.
- Regulatory side to hydrogen is unclear.
- We need more clarification on likely course of future propulsion types.
- 'Chicken and egg' challenge with vessels and fuels.
- Over-capability on vessels is a big barrier to innovation. If vessels are built to deal with 1% scenarios then new fuels and batteries can't meet requirement.
- Most barriers are related to cost.
- If one wind farm operator chooses ammonia, another chooses hydrogen then the vessels will not be able to move between wind farms.

2. Who are the solution providers, who can fix the problem and remove the barrier?A

- Longer charter mechanisms are needed.
- Look at seabed leasing, could change be forced here rather than putting responsibility on the developers.
- Regulation could be an enabler.
- Certainty could be embedded into license conditions. CO_2 budgets for installation programs.
- Data sharing is crucial, particularly on costs and looking at where CO_2 emissions arise.
- We need to be working towards a common objective, we need to move from softer objectives towards something more mandatory to get that level playing field.
- Alongside the question of, can we build a net zero ship we need to consider whether we can build a net zero port.
- Technology is new and costly can we look at subsidies?

- We need to accelerate collaborative thinking on infrastructure.
- Classification societies and IMO could sort clear guidance.
- Designing technology agnostic power trains.
- Wind farm charging would unlock a lot of technologies.
- Emissions savings can come from limiting vessel movement, this can come from remote blade inspection.
- Tackle the financial barrier of high investment costs. There is certainty needed.
- We need regulation, there are currently no regulations for hydrogen.
- Collaboration is essential.
- The Fuel cost differential will require a collaborative effort. Industry must enforce environmental cost indicator in RFQs.
- Joint investment in vessel technology between customer and vessel operator.
- An Incremental roadmap is needed.
- We need to be data driven.
- We need to start at the highest level, looking at the leasing of these areas.

At the end of the session attendees were asked where asked whether they could see net zero maritime logistics by 2030. The results were clear, although only one attendee saw this happening without intervention, the vast majority believed it was a possibility but only with significant policy intervention and joined-up industry leadership'.

Table A5-3: Poll results from the industry engagement event (basis of 39 respondents).

Question	
Can North Sea offshore wind O&M achieve net zero maritime logistics by 2030?	
Option	Result
Yes, we're on course.	3%
No.	15%
Yes, but only with joined up leadership from industry (OSW owner/operators and original equipment manufacturers).	10%
Yes, but only with significant policy intervention from governments.	0%
Yes, but only with significant policy intervention and joined up industry leadership.	72%

7 Phase 2: Stakeholder Interviews ResultsA

To support industry and advise government, analysis of the stakeholder interviews is of paramount importance. Opinion trends, key barriers and enabling actions have been identified to produce relevant conclusions that accurately represent the views expressed by the sample of industry stakeholders we interviewed.

7.1 Limitations

One of the limitations of the results is that the sample of stakeholders interviewed is not an exhaustive list of industry representatives. More work could be done to formally consult with a wider group of industry representatives on specific focus areas in order to further explore the issues raised here.

A further limitation is that there is a divergence of opinion on some topics which makes it difficult to capture a 'common industry view. A good example here is with regard to the future of CTVs and the question of future fuel source. Our interviewees included a range of both CTV designers, shipyards, operators and charterers. Within this sample group there were some who expressed a view that hydrogen/ammonia would be the likely future fuel source for CTV, whilst others expressed support for electric/hybrid diesel electric CTV.

7.2 Stakeholder Interviews Section 1A

Section 1 investigated details of the organisations and individuals being interviewed. Results provide an oversight of the experience of the individual(s) interviewed (several organisations provided multiple representatives for the interview in order to enable responses to the range of technical, commercial and regulatory questions), active business areas covered and location of operations. The data highlights the variety of companies interviewed and will be used to present views specific to business areas. Figure A5-4, Figure A5-5 and Figure A5-6 present the frequency of active business areas, organisational roles and location of operations respectively.

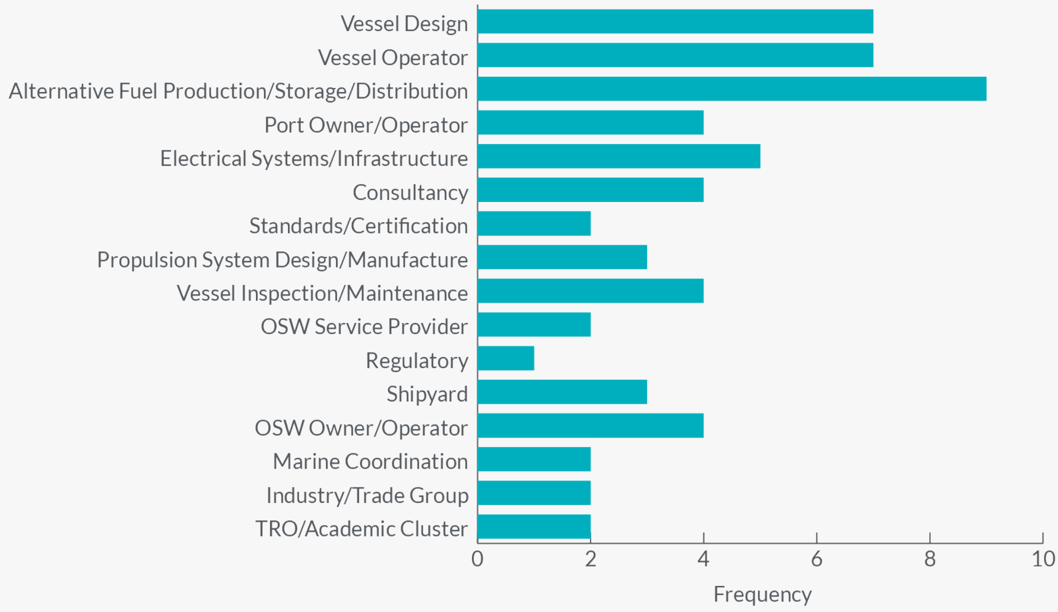

Figure A5-4: Frequency of active business areas interviewed (basis of 27 organisations).

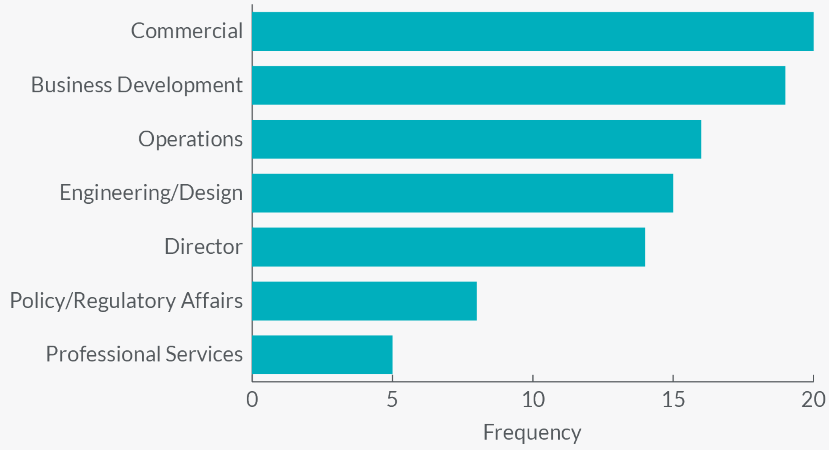

Figure A5-5: Frequency of company roles interviewed (basis of 27 organisations).

Figure A5-4 and Figure A5-5 highlight the wide range of organisations and business roles that were interviewed. This is significant when evaluating the report's findings as it confirms that the concluded opinions are a reliable and informed representation of industry. The frequency was recorded by offering the interviewees an opportunity to state relevant active business areas and their role within the company. Participants were provided a pre prepared list with the added option of an "other" category, thus allowing unique roles/active business areas to be suggested.

Figure A5-6 confirms that there was diversity of location regarding the companies base and main area of operations. The range of diversity limits regional views and echoed opinions thus validating the usefulness of the results. The figure shows that organisations were wide spread throughout the UK, however there were limited sources from the EU. Involving more EU industry in future stakeholder investigations is recommended to aid the collaboration process that maritime decarbonisation requires.

Figure A5-6: Map showing the head office and locations of operations for the organisations interviewed (Orange: Head Office, Red: Port and Green: Operations) (basis of 27 organisations).

7.3 Stakeholder Interviews Section 2 – Port Owner/OperatorsA

Section 2 sought the thoughts and opinions of port owner/operators along with providing details regarding port infrastructure (requests and plans), key barriers and an approximate timeline of any planned clean maritime infrastructure upgrades.

7.4 Port Infrastructure RequestsA

Concerning requests from port clients for port infrastructure upgrades, it was a clear theme that most of the requests were linked to alternate fuelling Infrastructure development. Regarding submitted requests, there was a mixture of experiences. Not all port owner/operators had received formal requests, however all port operators reported that they had in the past had, or were currently involved in ongoing discussions with clients/prospective clients about infrastructure upgrades to enable clean maritime operations. Interviewees indicated that there is significant interest in alternative fuels and that there was particular demand for hydrogen infrastructure. Participants also discussed the implementation of other alternate fuelling infrastructure linked to biofuels, LNG, shore power charging and modular battery systems.

7.5 Port Infrastructure Upgrades

The comments on port upgrades were of a progressive theme as there is a variety of planned port upgrades and all port owner/operators were open to the idea of driving clean maritime investments. Interviewees reported that port hydrogen infrastructure should be available between 2021 and 2025 to support a known, specified demand. There were also suggestions of port electrification by 2023, however not necessarily supplied from green sources.

7.6 Port Investment BarriersA

The comments on port investment barriers were broken down into four categories: Investment risk, technology uncertainty, lack of standardisation/regulation and port collaboration.

A common theme throughout the interviews was risk of investment. Interviewees stated that the funding required to undertake infrastructure upgrades is high, it is not clear where the investment should go and that the risk of investment is substantial.

An equally widespread theme during the interviews was that the lack of regulations in place further deterred investment. Port owner/operator's expressed that the lack of standardisation caused concerns over the security of invested infrastructure.

Technological uncertainty was a frequent theme during the interviews which links with risk of investment. Industry stated that technology uncertainty is leading organisations to refrain from investing as other routes may prove favourable, consequently isolating their assets.

The final notable topic was port collaboration. Participants suggested that municipal port ownership has a positive effect on investment in infrastructure. It enables a longer-term view to be taken on investment return along with a unified approach between industry, society and government (at either national, regional or local level) to fully support decarbonisation.

Overall, port owner/operators are beginning to receive requests for infrastructure investment to support clean maritime operations. There are confirmed plans to upgrade some ports with alternate fuel infrastructure, often with an emphasis on hydrogen and shore power. Regarding the investment barriers, participants expressed concern over investment risks, technological uncertainty, lack of regulation and port collaboration. Industry is deliberating investment as they want to avoid financing unfavoured technology and therefore isolating their assets. Port owner/operators also discussed port collaboration. It was stated that port municipality was a positive driver for clean maritime as the unified approach encourages support for clean maritime infrastructural investment.

7.7 Stakeholder Interviews Section 3 - Maritime Energy Infrastructure System Developers/Owner/Operators (inc. Electrical/Alt fuel products and systems)

Section 3 sought the thoughts and opinions of maritime energy infrastructure system developers, owners and operators along with capturing key details regarding order requests, planned developments and the major barriers to investment.

7.8 Requestions and Planned DevelopmentsA

The comments on requisitions and planned developments were of a positive nature. All stakeholders acknowledged that they had active requests and lots of conversations on going. Commentors stated that the following energy infrastructure systems were in the discussion and being requested: Conversion of diesel bunkers to support LNG, offshore battery systems, electrolysers, low carbon diesel infrastructure, shore power and ammonia systems.

Regarding planned developments, participants suggested that they were planning on developing hydrogen storage tanks, fuel bunkering facilities and portside battery charging systems. There was concern over the commercial, regulatory and technical challenges involved in the transition to alt fuels such as ammonia and hydrogen, as this would require a complete overhaul of infrastructure. Stakeholder's time scaled comments suggested that numerous technologies would be employed with battery technology and pilot scale ammonia being readily available by 2024. It was also mentioned that ammonia and hydrogen systems on a commercial scale would be accessible closer to 2028 and 2030+ respectively.

7.9 Maritime Energy Infrastructure System Investment BarriersA

The comments on maritime energy infrastructure barriers were broken down into the following themes: Financial concerns, logistical issues and lack of government regulation.

The most frequently discussed topic throughout the interviews was the financial risk of investment. Stakeholders stated that because the infrastructure is expensive to implement then the servicing fees must be high to account for this, however this deters users. To counter these financial concerns, industry said that government investment support is required to finance projects and that horizontal collaboration throughout the industry will benefit all parties and help reduce cost.

Another frequent subject for conversation throughout the interviews was logistical issues. Stakeholders highlighted that there are a variety of issues that need to be overcome to enable the investment. The first logistical issue is space constraints. Commentors suggested that the infrastructure requires large amounts of space, which isn't always available at ports and that it can be difficult to get planning permission. Another logistical concern was the undeveloped alt fuel supply and grid constraints. It was stated that without the alternate fuel/power supply being available assets can be left stranded and inactive whilst they wait for a suitable supply. The last logistical concern stated by participants was that the fuels can be difficult to store, distribute and use, and that safety considerations must be made.

The final theme during the conversations was in regards to the lack of government policies in place across the North Sea region. Industry indicated that there was very limited regulatory/ incentive support which is essential to facilitate a business case. Participants suggested fuel incentives and capital investment grants could be effective to drive market adoption.

7.10 Stakeholder Interviews Section 4 – Vessel Designer/Builders (including sub-system/propulsion system)

Section 4 targeted vessel designers and builders to develop an understanding of their business direction and the barriers faced by industry. Collectively the interviewees were responsible for the design and build of SOV's, CTV's, WDV's and sub systems such as propulsion, microgrids, control and automation.

Regarding requested vessels and available design types, the stakeholders had received orders for the following vessels: Hybrids CTV/SOV, alternate fuel CTV/SOV and electric CTV/SOV. It was made apparent that multiple organisations had orders for hybrid vessels and active foil diesel systems in 2021 with the potential for a couple fully electric vessels nearing 2022.

Although poll results showed a large variance in how vessel builders/designers rated the barrier of range anxiety, clarifying comments showed that the perception of the issue was quite common. Vessel designers generally accepted that the energy density of low carbon fuels and batteries posed a limitation to the current prospect of designing vessels that could run solely on this technology. Although vessel designers pointed out that there was little, they could do about the energy density as this was dependent on technological advances from outside of their industry, they pointed out some areas that they could improve the situation. Energy efficiency measures such as better hull designs, advanced engine control systems and upgrading onboard electronics can all reduce power demand and thus make better use of available fuel/electricity. Consensus was that as these measures were likely to reduce costs whatever fuel system was used, demand for them is likely to high without intervention. An area that could see improvement however was the collection of real worlds operations data. Vessel customers were unsure of the exact power demands the vessel would require, which meant that range and power demand specifications could be ruling out lower carbon options for want of better data.

Cost of low carbon systems was seen as a barrier to adoption. Although vessel builders naturally saw subsidies and incentives - especially for first movers - as a good idea, there was an appreciation that for zero carbon vessels to see widespread adoption they must be able to 'stand on their own feet' in the long run. Ideas for how this could be done centred on two themes. Legislating mandatory carbon emissions limits or a tax framework that would make low carbon fuels cost competitive with traditional fuels.

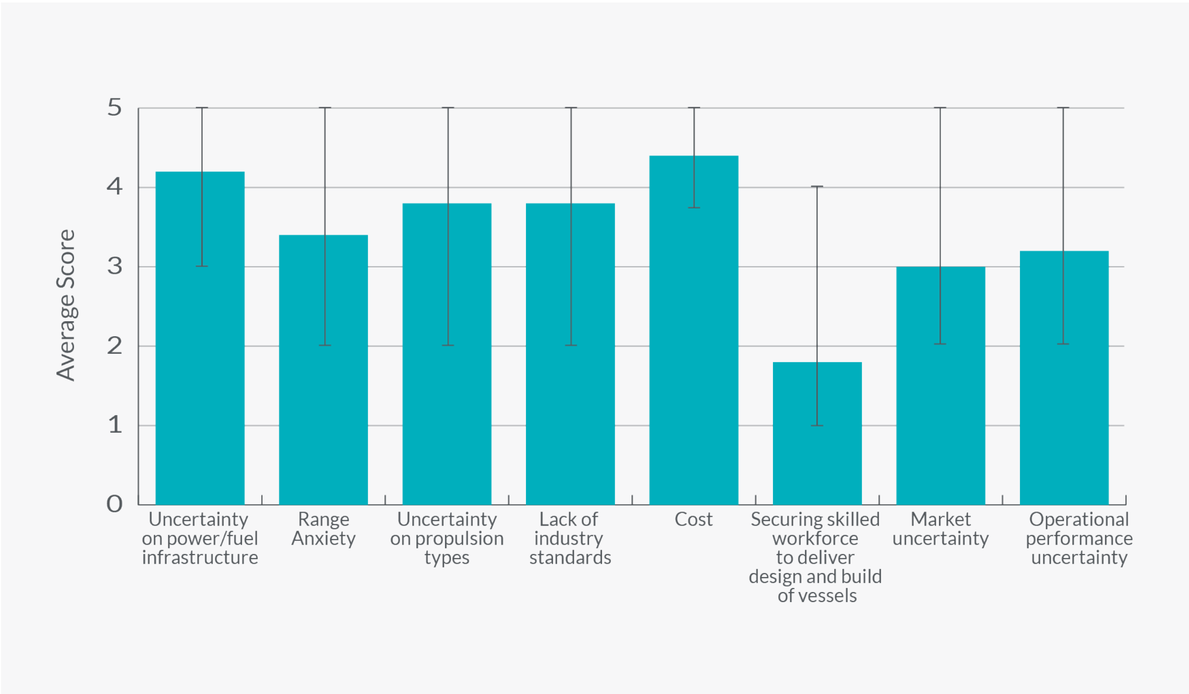

Figure A5-7: The average scores provided by the interviewees for each challenge (error bars show maximum/minimum values and is on a basis of 5 organisations).

7.11 Stakeholder Interviews Section 5 – Vessel Operator/ClientsA

Section 5 targeted the thoughts and opinions of vessel operators/clients along with providing details involving current fleet operations. Information was provided concerning size of fleet, location of operations, fuel consumption, emissions, fuel sources, vessel lifetime, typical charter duration and transition timescale.

7.12 Vessel Operation Strategy and Clean Maritime BarriersA

The comments on vessel operation strategies and clean maritime barriers were broken down into four categories: Optimising vessel strategy, industry collaboration, future vessel selection and vessel development & technology uncertainty.

The most common theme throughout the comments was that vessel operators/clients recognised the importance of vessel strategy and how it can significantly reduce emissions. This included decisions on vessel type and combination selection, O&M strategy and voyage planning/route optimisation. Ideas of joint planning and AI systems circulated the conversations with the suggestion that organisations could collaborate to reduce milage inefficiencies and that computerised systems could calculate optimised routes to execute operations. Many of the interviewees confirmed their awareness for route optimisation and that they are currently reviewing their operations strategies to reduce emissions and OPEX.

There were several references to vessel development and technology uncertainty. Participants expressed a variety of alternative fuels and technology that are available however, they desire compatibility throughout the industry to avoid redundant/stranded assets and the risk of investment associated. Technologies and vessel development regarding electric crew transfer vessels (ECTV), hybrid and hydrogen systems were discussed throughout with no preferences identifiable.

Industry collaboration was another popular theme. Throughout the categories there tended to be an element of collaboration and cooperation linked to the ambiguous solutions. The vessel operators/clients talked about joint endeavours with greater guidance from clients (wind farm owner operators/OEMs) to help steer preferences for SOV/CTV and support in bringing industry together to jointly plan infrastructure development and offer guidance to designers and manufacturers, thus reducing cost and encouraging investment and development.

Regarding future vessel selection it was acknowledged that extensive SOV's operations (with daughter craft) will be essential to support larger sites further from shore, and a growth in SOV numbers in the North Sea is anticipated in the years ahead. Concerns were expressed about how sea conditions can limit daughter craft capabilities. However it was also stated that larger CTV's operating on extended rotation periods (~14 days) could offer an effective solution, though some form of offshore power supply would be important to support these extended periods of rotation for CTV

Un-crewed vessels, operated from remote operations centres were seen as a technology likely to have more widespread adoption in the future. Without the need to carry personnel vessel sizes could be reduced, this would deliver carbon savings both in terms of lower operational power requirements and the increased opportunity for battery electrification that this would allow. Although this is seen as a future growth area, widespread adoption of unmanned vessels is still more at the experimental stage and will require more significant large scale demonstrations as well some clarity over legislative questions.

Overall, vessel operators and clients recognised the importance of vessel strategy and how the optimisation can significantly reduce emissions and cost. There were numerous accounts of organisations reviewing their procedures and looking for new optimisation solutions through digital voyage planning/route optimisation tools and industry joint planning schemes. Industry described that their hesitation with investment was due to the lack of technological certainty.

A collaborative direction throughout industry would enable the transition to clean maritime operations and instil confidence throughout the vessel operators/clients. Lastly, stakeholders described the importance of SOV operations in future O&M strategy with CTV's and daughter craft operating in conjunction.

7.13 Vessel Investment Barriers

The comments on vessel investment barriers were broken down into four categories: Infrastructure standardisation, retrofitting ability, technology development uncertainty and short charter durations.

A widespread theme throughout the interviews was that technology development uncertainty was a major barrier for organisations to invest in vessels. All of the technology uncertainty was linked to fuel/power options, where industry were unlikely to invest in systems that may lack compatibility across different ports and/or wind farms. This question of compatibility is a major concern given the transient nature of operations and relatively short charter durations (particularly in the case of CTV). With regards to specific fuel/ power sources the interviewees expressed that battery power density and limited endurance caused concern and that hydrogen/ hybrid options are popular but there are associated inefficiencies.

Infrastructure standardisation was a popular theme during the interviews. Closely related to technology development uncertainty, the vessel operator/clients stated that infrastructure is not available/standardised thus causing problems throughout the supply chain. The lack of standardisation makes it risky for industry to invest as there is little or no infrastructure in place to support their investments. To successfully invest they rely on a secure demand with the knowledge that their selection of technology will be compatible.

A number of stakeholders highlighted apprehensions regarding the length of charter durations. Longer charters were preferred by the vessel operators/clients as it enables investment with a greater degree of security and is attractive to lenders whose support is in most cases essential in providing the finance needed to build vessels.

Participants addressed that charter contracts are in some cases shortening and that clients are transitioning to "self-maintenance" of wind farms sooner than was traditionally the case. This means that the owner operator will often go to the market for SOV services independent of the turbine OEM sooner than might otherwise have been the case had they extended the turbine OEM service period. Consequently SOV charters can be shorter than previously experienced under extended OEM service models, creating challenges for the industry. The required charter duration is different between CTV's and SOV's. Typically SOV's need a charter contract of 10 years or more to support the investment and CTV's ideally require charters over 7 years, however a minimum of 5 years is essential to investing in clean maritime.

With regards to retrofitting there was a frequent theme that there is immediate potential to retrofit old vessels however in the long term, bespoke new builds are currently favoured. Overall, industry showed openness to the idea, however there were concerns. The interviewees stated that uncertainty over alternate fuels and that the cost benefit analysis are worse in some cases make it risky to invest and retrofit.

To summarise, vessel operators and clients highlighted four major investment barriers, infrastructural standardisation, retrofitting ability, technology development uncertainty and short charter durations. Infrastructural standardisation and technology development uncertainty were very frequent barriers throughout the dialogues. Industry doesn't want to invest in a technology without the security that their vessels will be compatible with a standardised infrastructure. Charter durations also need to be lengthened to encourage investment. The organisations commented that longer contracts are attractive to lenders and that SOV's and CTV's require a minimum 10 and 5 year contract respectively, to validate a newly built vessel. There was a significant response regarding retrofitting and many were open minded, however concerns over longevity were common.

7.14 Maritime Decarbonisation InnovationA

The comments on maritime decarbonisation innovation were broken down into 2 categories: Alternate fuel usage and electrical charging.

A very strong theme throughout the topic of clean maritime innovation was associated with alternate fuels. Industry discussed the following maritime alternate fuels/systems: hydrogen, biofuels, solar, wind power, electric/battery power, hybridisation and methanol. The most common fuels mentioned were hydrogen, hybrid and electric systems. Organisations emphasised that hybrid, battery/electric and hydrogen powered vessels are already on the market and are commercially available however there are concerns regarding weight/endurance of batteries.

Offshore charging was another popular theme throughout the interviews. Offshore electrical charging systems were commonly discussed as the interviewees firmly emphasised that it is a requirement for electric/battery powered vessels.

Throughout the discussions the "chicken and egg" dilemma was used as a very popular analogy. Vessel operators do not want to invest in clean maritime vessels if there is no infrastructure to support them. The same is applied to port/offshore wind owners, they do not want to invest in infrastructure when there is not a clear and identifiable demand.

Autonomous vessels and alternative fuel infrastructure were also raised. Contributors stated that autonomous vessels were already in operation and there are demonstrations of alternate fuelled autonomous vessels. Concerning the alternate fuel infrastructure there was reference to an established 400 kW electrolyser located in Brande and a launched 1 MW electrolyser, hydrogen storage and fuelling station in the port of Antwerp.

Contributors clearly voiced a recognition for alternate fuel being demonstrated and commercially available. The comments focussed on hydrogen, hybridisation and electric/ battery powered vessels as examples of clean maritime innovation, including hydrogen fuelling infrastructure such as, electrolysers, hydrogen storage and fuelling stations. Alarms were raised regarding the battery power density, weight and endurance, however this was connected with offshore charging demonstrations and projects that are considered vital to enable battery/ electric technology. Lastly, industry briefly discussed autonomous vessel potential.

7.15 Stakeholder Interviews Section 6 – Consultants, Academia, Clusters and Trade Groups

Section 6 investigates the work and research being completed by consultants, academia and trade groups that supports maritime decarbonisation. The section reviews project specifics and aims to determine the main barriers and enablers to decarbonising North Sea offshore wind maritime logistics.

7.16 Programmes of Work and ResearchA

The comments on work and research that supports maritime decarbonisation were categorised by the following 3 themes: Alternate fuels, offshore/onshore infrastructure and data standardisation.

Alternate fuels was the most popular topic for conversation. An overwhelming majority of interviewees were involved in research or work investigating the use of alternate fuel for a variety of vessel types. A range of alternate fuels including, hydrogen, ammonia, electrification, flow batteries, LNG, methanol, Di-methyl ether and biofuels circulated the discussions, however there was particular emphasis on hydrogen potential. Several demonstrations/projects of alternate fuelled vessels were also amongst the responses, notably, the Hydrocat, Raptor 2100, Hydrotug and Hybrid SES.

Vessel data standardisation, considering emissions and fuel consumption, was a popular theme. Participants made apparent that benchmarking work and data research was underway. Participants suggested that ports and vessel operators need to collaborate data usage to enable optimised operations and support decarbonisation.

Industry stated that there was work and research happening with regards to offshore/onshore infrastructure. Strictly offshore, stakeholders discussed 2 programmes of work: an E loading buoy project and offshore charging standardisation research. Regarding onshore infrastructural work, interviewees highlighted a couple examples of present research. Commentors described investigations on the uses of onshore power vessel charging and onshore power for hydrogen and ammonia generation.

It is clear that consultants, academia and trade groups are investing in work and research to support maritime decarbonisation. The primary focus tends towards alternate fuel technology, however there is also significant focus in data standardisation and offshore/onshore infrastructure. Participants described a range of current work including alternate fuel demos (Hydrocat, Hybrid SES, Hydrotug and Raptor 2100), data benchmarking research and offshore technology projects (E loading buoy and charging standardisation research).

7.17 Barriers and EnablersA

The stakeholders considered a variety of key barriers and enablers during the interviews. The barriers and enablers can each be broken down into 3 themes. The barrier related themes were fuel uncertainty, risk on investment and logistics whereas the enabling themes were Industry collaboration, port infrastructure investment and increased charter duration.

A common suggestion from interviewees was that fuel uncertainty slows the adoption of new technologies as organisations don't want to isolate their assets. It was also mentioned that the wider range of fuels used would slow production and development of the vessels.

Regarding the logistic issues, participants made clear that alternate fuel supply is a key barrier regarding the development of infrastructure. The "chicken and egg" dilemma resonated throughout the interviews. Vessel designers/builders do not want to produce alternatively powered vessels if there isn't infrastructure and a fuel supply to support them.

A frequent enabling action during the conversations was that industry collaboration is essential to aid the transition. Interviewees discussed collaboration between port OO's and vessel OO's, government and port OO's and port OO's grid networks. It was stated that organisations expect other to be first mover when in reality a cooperative approach is needed.

7.18 Stakeholder Interviews Section 7 & 8A

Sections 7 and 8 investigated the opinions and thoughts of all interviewees regarding key enabling actions. All respondents were asked questions about enabling factors to support the transition to clean maritime operations in offshore wind in three areas:

- Key enabling technologies;
- Key enabling changes to policy/regulation;
- Key enabling actions that could be taken by industry (specifically wind farm owner operators or turbine OEMs as these are the ultimate charterers of vessels or clients of those ho charter the vessels).

As well as commenting on the importance of a range of listed 'enablers', interviewees were asked whether they had any additional ideas of enablers that should be taken into account in identifying actions and barriers to enable maritime decarbonisation.

7.19 Key enabling technologiesA

The comments on enabling technologies were broken down into four categories: Infrastructure needed, Benefits of low carbon 'fuels', Limitations of low carbon fuels and technology preferences.

The most common theme for comments was that the infrastructure to supply low carbon fuels and electric charging was not in place, this included bunkering and electrical connections both offshore and in port. Where electric charging facilities were available in port there was concern over whether sufficient electricity supply was available to meet demand (both now and in future), similarly low carbon fuels prompted concerns about availability for potential future demand. Within offshore charging one commentor raised concerns about the need to determine who will be selling the power, and another commented that multiple charging points would be beneficial. As to whether Offshore or onshore charging was a higher priority, although commentors had strong opinions on this, they were split between the two options.

Several commentors thought that deployment could be driven by some of the benefits that were obtainable from offshore charging. Offshore powering of SOVs could allow them to stay at sea longer, and also act as charging docks for smaller vessels. Autonomous technology (Vessels, drones...) was suggested as a particular beneficiary of offshore power and their increased deployment could decrease personnel costs, though their supplication is limited and there was no suggestion of the elimination of human involvement in O&M. Finally, one commentor was interested in the idea of using off-peak power at low or even negative cost.

Concerns over limitations of low carbon fuels were widespread and consistent. Primarily the ability of low carbon fuels to deliver energy and power densities comparable to traditional propulsion systems. Other concerns included Hydrogen fuel cells having limited power outputs, fire risk with battery systems and increased capital costs.

Although several commentators showed clear preferences for particular technologies there were few consistent trends. Arguments for both onshore and offshore fuelling were advanced with onshore fuelling tending to be suggested as an easier option. With regards to fuel types although enthusiasm was shown for electric charging, lower carbon combustibles were seen as a more realistic proposition in the near term.

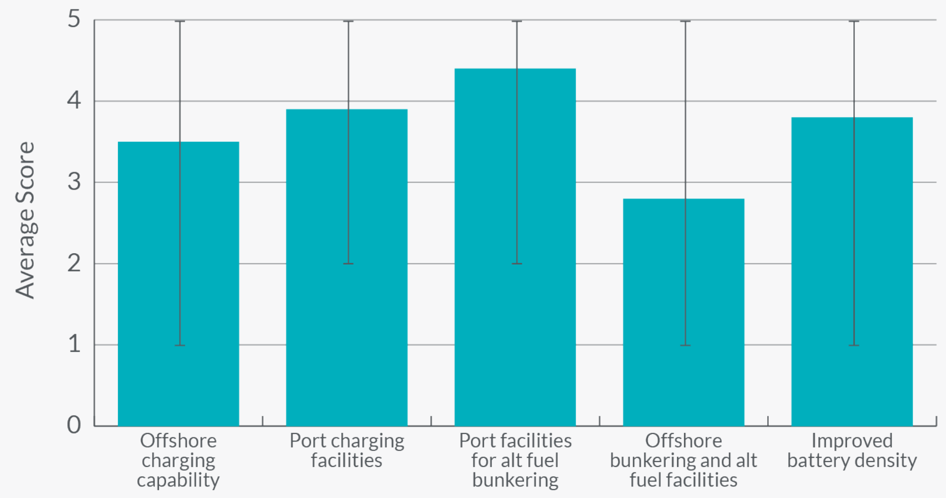

Figure A5-8: The average scores provided by interviewees for the key enabling technologies (error bars show maximum/minimum values and is on a basis of 27 organisations).

The need for widespread fuelling infrastructure was seen as the most pressing concern in the roll-out of clean maritime technologies, this applied to all low carbon fuels. There was widespread enthusiasm for the potential benefits that could be delivered by on and offshore electric charging, however in the short-term, due to range/weight anxiety, this was focussed on vessel's hotel and auxiliary operations, with propulsion only seen as viable for short journeys near charging points or for smaller vessels such as CTV or daughter craft. For this reason, particularly with regard to SOV operations, alternative combustion fuels are generally seen as a more deployable proposition in the short-term.

Key enabling changes to policy/regulationA

The comments on enabling policy/regulation were broken down into six categories: Incentives, Availability of Fuel, Clarity of pathway, Regulation, Wider Economy, Targets, R&D

The most common comment made was a desire for incentives to encourage movement toward clean maritime technology. Although incentives were requested over a wide range of areas, the most common was for incentives targeted at removing the CAPEX expenditure risk, particularly for first movers/early adopters of innovative technologies.

In particular, respondents expressed a strong desire for capital support to encourage the development of alternative fuel and electrical charging infrastructure. This was seen as necessary to address the market barriers often described in terms of 'chicken and egg', whereby port owner/operators were unable or unwilling to invest in port infrastructure without an identified offtake demand for the alternative fuel/electrical charging, and vessel operators wishing to invest in bringing new clean maritime vessels to market are unable to make investment decisions because of uncertainty over the widespread availability of affordable fuel/power.

According to stakeholders interviewed, intervention from governments could take the form of direct funding, tax breaks or underwriting risk. It was also suggested that this risk would be reduced if an OPEX incentive for long-term fuel cost reduction was in place to incentivise the use of alternative fuels/electric vessels. To a lesser extent it was suggested that disincentives could also be used to encourage reduction of fossil fuel usage, such as higher carbon taxation. Commentors referred to schemes used in other sectors that they saw as being successful such as the Renewable Heat Incentive and carbon taxation.

There was a widespread desire for Government to take a lead in suggesting which fuels might be in use in the future. Commentors suggested that they were ready to move in designing cleaner maritime systems but without clarity over fuel type the risk of stranded investment was currently too high. One commentator compared it to the VHS vs Betamax dilemma.

Availability of Fuel was a common concern for those involved in the design or operation of vessels. It was suggested that once a fuel had widespread and affordable availability, vessel design could follow quickly but without this guarantee it was difficult to justify this investment. Where expressed, this view was consistent across a range of alternative fuels.

Regulation was generally welcomed in comments across a wide number of areas, including safety, fuel distribution and storage and autonomous vehicles. Targets were such a common suggestion that they will be dealt with separately later. One commentor mentioned that regulating vessel speeds could be a quick win. There was a strong preference for common regulations to be enacted across the North Sea to ensure operations were not geographically constrained.

Targets were seen as a powerful way to enact change. With one exception Targets were suggested to be an essential component of decarbonisation. Many stakeholders described this as important both in establishing a 'level playing field' across the industry, and also in providing certainty to investors that clean maritime technology will be mandated and therefore offers a low-risk investment.

R&D was mentioned by several commentors however there was no clear theme as to what direction this should take, with preferences for both government intervention and industry led R&D.

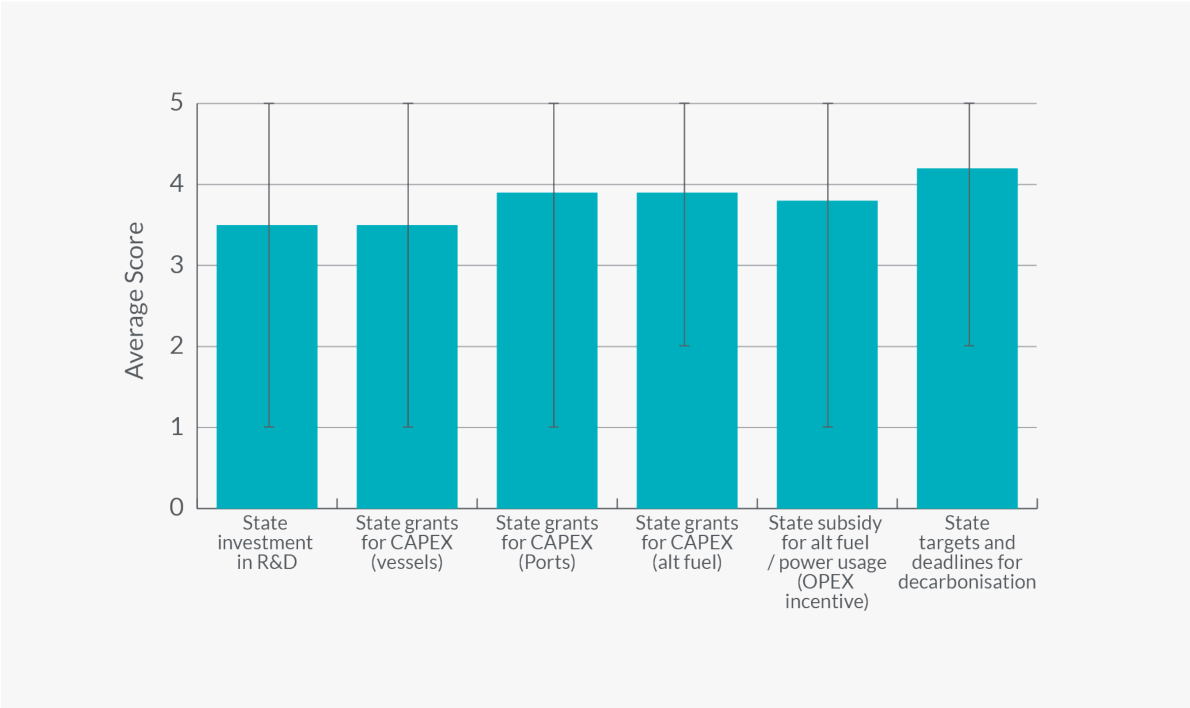

Figure A5-9: The average scores provided by the interviewees for key enabling policy and regulation (error bars show maximum/minimum values and is on a basis of 27 organisations).

Industry has expressed a clear desire for Government intervention to support the de-risking of clean maritime through policy and regulation, particularly in the early stages of development. The uncertainty over which fuel types will persevere is seen as a barrier to investment at scale. Although it seems likely that government intervention is needed to subsidise R&D costs and, in some way, underwrite CAPEX expenditure for first movers, this could be minimised if investors have confidence in fuel being available widely and at an affordable cost. Targets were described as highly desirable and often as 'essential' to decarbonisation which could provide much needed clarity for the industry. Further regulation, bespoke to the individual nature of emerging fuels, is widely seen as necessary. Where policy, regulation and targets are enacted it would be highly advantageous if this were done with a commonality of approach across the North Sea area.

Key enabling actions that Industry (wind farm operators and turbine OEMs) could takeA

The comments on enabling actions by industry were sorted into three categories: Collaboration, Long-term contracts and R&D.

Greater collaboration between wind farm owner operators/OEMs and the supply chain was seen as the greatest enabling action that industry could take. It was suggested that changes would be necessary throughout the supply chain to deliver clean maritime and thus these industries would need to work together rather than relying solely on procurement.

Collaboration between competitors was also seen as a benefit to mitigate risk and promote common standards, but one commentor noted that the element of competition made this difficult. It was noted that collaboration should not be constrained by national borders. Collaboration was viewed very positively as it would promote interoperability and risk could be shared across the industry.

The length of contracts was seen as a key roadblock in delivering investment as short-term contracts meant that CAPEX was at risk. This was commented upon across the industry but with particular regards to vessel tenders. One commentor noted that the longer-term contracts available in Belgium and the Netherlands had enabled greater investment in sustainable solutions.

Although R&D was again regularly mentioned, there was no clear consensus as to what direction this should take, with some commentors looking for greater R&D investment from industry whilst others thought that current levels were sufficient. Collaboration within R&D was seen as beneficial.

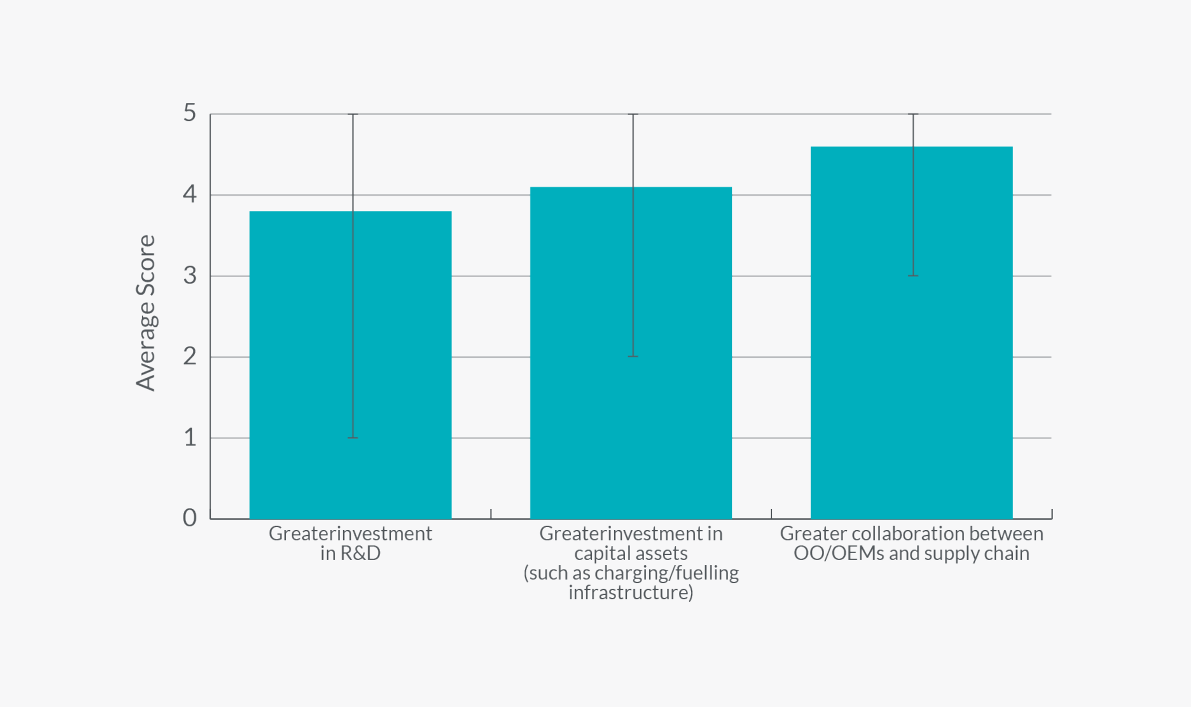

Figure A5-10: The average scores provided by the interviewees for key enabling actions (error bars show maximum/minimum values and is on a basis of 27 organisations).

The view as to how industry could enable clean maritime was clear. Collaboration both within the industry and across other sectors was seen as universally beneficial as it would enable interoperability and limit risk. It should be noted that this view came from interviews that were carried out by voluntary participants engaging with a body that promotes collaboration and so there may be some degree of selective bias. Promoting longer term contracts, particularly vessel tenders would appear likely to de-risk investment in clean technologies.

Other Factors

Other suggestions that commentors made and suggestions that did not fit with previous categories were collated and sorted into 4 themes, who should bear the cost/risks, funding streams, wider economy, and scale.

Some commentors raised the issue of costs and benefits not necessarily being shared equally between different areas of the industry. Those in the industry who were responsible for investing in vessels and port infrastructure were concerned that the benefits of this may be delivered to those who paid the fuel costs which, in most cases, is the wind farm owner operator.

Several funding streams for investment were identified, including equity investment, national and regional governments, and regional investment banks.

Some comments were made about how the industries outside of the renewable maritime sector.

It was noted that scale was an important factor in cost reduction and current small scales and the relatively smaller size of the marine propulsion industry meant that unit costs were likely to be higher unless larger scale production could be rolled out.

8 Phase 3: Stakeholder Workshop Results and DiscussionA

To support industry and advise government, analysis of the stakeholder workshops is of paramount importance. Opinion trends and additional key barriers have been identified in review of the preliminary findings. The workshop results were used to direct report modifications regarding barriers, technologies identified, enabling actions and model assumptions. The workshops were divided into 5 events each emphasizing a particular technology/industry, the 5 events covered the following:

- **Event 1:** Vessel Design and Build
- **Event 2:** Alternative Fuel Production and Distribution
- **Event 3:** Electrification, Charging Systems and Batteries
- **Event 4:** Offshore Logistics, Operational Performance and Enabling Infrastructure
- **Event 5:** Port Logistics and Enabling Infrastructure

8.1 Market Scenario Model EvaluationA

The clean maritime scenario and market model segment of the workshop aimed to present the methodology, assumptions taken and the results of the proposed model. Attendees were then given the opportunity to challenge and flag any potential errors or extra considerations. Criticism was scarce for this section of the report, however stakeholders commented on 4 key points.

- Include other green house gases in the emission modelling.
- Consider logistics and infrastructure in the fuel price estimates.
- Reduce assumed CTV loitering fuel consumption.
- Compare alternate fuels in the model (ammonia, methanol and HVO)

8.2 Technology Assessment

The technology assessment section of the workshop intended to introduce the current and future technologies research in the report. Attendees were given the opportunity flag any missed technologies and challenge the relevance of the technologies researched. A poll was held to evaluate how thorough the technology list was.

Table A5-11: Poll results from the stakeholder workshop (basis of 39, 11, 18, 15 and 6 respondents, for events 1 to 5 respectively).

Question					
How thorough is the list of key technologies for OSW Decarbonisation captured?					
Option	Event Result (%)				
	1	2	3	4	5
1, inadequate - Many major technologies missed	0	0	0	0	0
2, moderate - Captures some of the key technologies	38	9	33	13	0
3, thorough - Captures most major technologies	62	91	67	87	100

The results demonstrate significant support for the proposed technology list with a majority of participants denoting the list as thorough. Whilst no contributors opted for the inadequate option there was a considerable amount of votes cast for moderate.

8.3 Other Key Technologies and Accuracy Evaluation

To further investigate the results of the poll, ORE Catapult engineering experts reached out to the present stakeholders to understand which specific technologies were missed and should be included. The participants were very forthcoming and were able to identify the following technologies:

- Semi-SWATH.
- Wave piercing catamarans.
- Active foil systems.
- Molten salt reactors/atomic batteries.

- Active heave compensation.
- Wind assisted power.
- Modular batteries.
- TRL for each tech.
- Hydrogen power paste.
- Hybrid systems and engine types.
- Shoreside electrification technology (infrastructure: electrolysers, fast charging systems)

8.4 Barriers to Adoption, Market, Policy and RegulatoryA

The barriers to adoption session aimed to present the barriers concluded from the stakeholder interview to industry. Attendees were given the opportunity to provide feedback regarding the thoroughness, relevancy and accuracy and the barriers presented. The section used 3 polls and open discussion to evaluate the barriers. The first poll asked attendees to rank, in their opinion, the 3 most significant barriers that limit decarbonisation of the North Sea offshore wind.

Table A5-12: Poll results from the stakeholder workshop (basis of 35, 7, 10, 12 and 5 respondents, for events 1 to 5 respectively).

Question					
Of the barriers identified – which 3 do you consider to be the greatest impact in terms of limiting decarbonisation of North Sea Offshore Wind?					
Barrier	Event Results (%)				
	1	2	3	4	5
1. Cost differential between conventional and alternate fuels	16	14	8	14	17
2. Lack of knowledge of future fuel cost	3	0	4	4	0
3. Cost of capital investment	11	10	16	5	11
4. Limited profit margins available	1	0	6	6	0
5. Lack of clarity over fuel pathways	11	12	6	8	0
6. Disproportionate carbon pricing	0	2	4	4	0
7. Safety codes for new fuels and electrical marine charging	1	0	4	5	0
8. Lack of standards	0	0	2	5	0
9. Lack of targets and deadlines	4	10	2	1	0
10. Imperfect information about emissions	1	2	0	3	0

Question					
Of the barriers identified – which 3 do you consider to be the greatest impact in terms of limiting decarbonisation of North Sea Offshore Wind?					
Barrier	Event Results (%)				
	1	2	3	4	5
11. Existing port infrastructure	29	14	10	9	17
12. Portside electrical power constraints	4	12	12	11	22
13. Existing vessel lifetimes	4	10	6	3	11
14. Split incentives	4	2	2	1	6
15. Contract lengths	1	2	8	5	6
16. Fixed funding for existing and under development wind farms	1	2	2	1	0
17. Lack of horizontal collaboration	1	2	0	3	6
18. Structure of offshore wind farm asset	1	5	6	3	0
19. Lack of in field performance data	0	0	0	3	0
20. Bias towards existing technology	3	0	0	8	6
21. Balancing emissions reductions against minimising turbine downtime	3	0	0	8	6

There was support for every suggested barrier, however the poll demonstrates that participants considered a specific 5 barriers to have the largest impact. The 5 barriers flagged the most impactful were the following:

- **1.** Cost differential between conventional and alternate fuels
- **3.** Cost of capital investment
- **5.** Lack of clarity over fuel pathways
- **11.** Existing port infrastructure
- **12.** Portside electrical power constraints

8.5 Other Barriers and Accuracy EvaluationA

The second poll investigated the thoroughness of the barrier list by asking participants to choose inadequate, moderate or thorough.

Table A5-13: Poll results from the stakeholder workshop (basis of 33, 12, 11, 14 and 5 respondents, for events 1 to 5 respectively).

Question					
How thorough is the list of key industry barriers and risks captured?					
Option	Event Result (%)				
	1	2	3	4	5
1, inadequate - Many major barriers missed	6	0	0	0	0
2, moderate - Captures some of the key barriers	18	8	9	7	0
3, thorough - Captures most major barriers	76	92	91	93	100

The poll demonstrates that in each of the 5 events there was agreement that the proposed barriers had a thorough coverage. To further investigate the results of the poll, ORE Catapult reached out to the present stakeholders to understand which specific barriers were missed and should be included. The participants were very forthcoming and were able to identify the following barriers:

- Component logistics and part sourcing from overseas.
- Port land constraints (note the high value of land and the competitiveness to occupy).
- Offshore versus onshore fees.
- Class societies battery approval time.
- Financials from a port perspective (where is the return)
- Avoid pressurisation of developers so they don't take business elsewhere.

The final poll of this section evaluated the accuracy of ORE Catapults barrier ranking system by asking stakeholders how accurate they thought the assigned scores were.

Table A5-14: Poll results from the stakeholder workshop (basis of 31, 11, 11, 14 and 4 respondents, for events 1 to 5 respectively).

Question					
How accurate is our assessment of the impact of various barriers?					
Option	Event Result (%)				
	1	2	3	4	5
1, inadequate - Few barriers assessed accurately	3	0	0	0	0
2, moderate - Some barriers assessed accurately	19	27	27	7	0
3, thorough - Most barriers assessed accurately	77	73	73	93	100

The poll confirms a high accuracy of rankings with the majority of participants in support of the scores delegated. To further investigate the poll results, ORE Catapult reached out to the attendees to understand which scores they disagreed with. The participants were very forthcoming and were able to identify the following barriers:

- Portside infrastructure rating could be higher.
- Policy/regulatory ratings seem inflated.

8.6 Roadmap and Enabling ActionsA

The final session of the events focussed to present the proposed roadmap and potential enabling actions. Attendees were given the opportunity to provide feedback regarding the thoroughness, relevancy and accuracy and the enabling actions presented. The section used a poll and open discussion to evaluate the actions. The first poll asked attendees to evaluate the thoroughness of the list of enabling actions.

Table A5-15: Poll results from the stakeholder workshop (basis of 12, 13 and 5 respondents, for events 3 to 5 respectively).

Question			
How thorough is the list of enabling actions captured?			
Option	Event Result (%)		
	3	4	5
1, inadequate - Few barriers assessed accurately	0	0	0
2, moderate - Some barriers assessed accurately	33	0	0
3, thorough - Most barriers assessed accurately	67	100	100

It should be noted that results for event 1 and 2 are not included in Table A5-15 as the poll was an added metric after reviewing the initial events. The results demonstrate significant support for the proposed enabling actions list with a majority of participants denoting the list as thorough. Whilst no contributors opted for the inadequate option there was a some votes cast for moderate.

8.7 Other Actions and Accuracy Evaluation

To further investigate the results of the poll, ORE Catapult reached out to the present stakeholders to understand which specific enabling actions were missed and should be included.

The participants were very forthcoming and were able to identify the following actions:

- Retrofitting incentives.
- Environmental performance standard.
- Training support for sea farers.
- Engagement with wider maritime industry.
- Look to other industries i.e. oil and gas to invest.
- RTFO style incentives.
- Zero emission vessels as a mandatory factor in sea bed auctions.
- Investment support at ports.
- Involve national grids.
- Network upgrades – upgrade capacity in a modular way instead of large bulk upgrades.
- Strategic investments with gov funding i.e. invest in ports that can also support other sites.

LIST OF FIGURES

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ENDNOTES

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