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Quantifying the impact of Robotics in Offshore Wind

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ABBREVIATIONS

AI	Artificial Intelligence
ASV	Autonomous Surface Vessel
AUV	Autonomous Underwater Vehicle
BSI	British Standards Institution
BVLOS	Beyond Visual Line of Site
CAA	Civil Aviation Authority
CAPEX	Capital Expenditure
CTV	Crew Transfer Vessel
DECEX	Decommissioning Expenditure
DEVEX	Development Expenditure
H&S	Health and Safety
IoT	Internet of Things
IRM	Inspection, Repair and Maintenance
ISO	International Organisation for Standardisation
LCOE	Levelised Cost of Energy
LEP	Leading Edge Protection
LPS	Lightning Protection System
MCA	Maritime and Coastguard Agency
ML	Machine Learning
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
OEM	Original Equipment Manufacturer
O&M	Operations and Maintenance
OPEX	Operational Expenditure
ROV	Remotely Operated Vehicle
SOV	Service Operation Vessel
UAS	Unmanned Aircraft System
UKRI	UK Research and Innovation
USV	Unmanned Surface Vessel

EXECUTIVE SUMMARY

The Offshore Renewable Energy Catapult (ORE Catapult) and KTN are commissioning several 'Industry Insight' studies as part of the Offshore Wind Innovation Hub (OWIH). These aim to provide a better understanding and more clarity in key topics such as the need for technological innovation in the pursuit of the reduction of energy costs, health & safety improvement and establishing the greatest benefit to the UK economy.

This report provides the results and analysis from a stakeholder engagement exercise for the offshore wind robotics industry, carried out by Xodus, ORE Catapult and the ORCA Hub. The report includes a quantitative analysis of the cost reduction opportunities that robotic applications can have in the operations and maintenance (O&M) of offshore wind farms with respect to the operational expenditure (OPEX), availability and levelized cost of energy (LCOE).

A concise stakeholder engagement exercise with 22 deep dive interviews with cutting edge researchers, robotic technology developers and service providers of aerial, marine and turbine crawler applications was conducted. This exercise identified the current strengths of robotics, including reliable remote operating vehicle (ROV) applications, autonomous underwater vehicle (AUV) applications, the use of unmanned aircraft systems (UAS) for offshore wind blade inspections and the huge potential of resident robotic systems. Some areas deemed in need of improvement include better definition of the economic benefit of robotics, improvements in the readiness of different robotics technology, appropriate regulation and common standards, social aspects and a stronger central supply chain interface.

Realising and overcoming the above barriers will enable the creation of the scenarios envisioned by the interviewees, which include: an increased number of robotic applications within the coming decade (2025-2030), applications of semi-autonomous systems in 2030-2040, full autonomy and resident systems from 2040 onwards, leading to the plant of the future that will include a feedback loop into the offshore infrastructure design process for greater improvements.

Using the above findings, a cost modelling analysis comparing the current state-of-the-art of offshore wind farms, as defined by the expert interviews, concluded that:

For a fixed wind farm, the potential cost savings for all the different scenarios and timelines range from up to 9.5% in OPEX reduction (3.5% in terms of LCOE) by the end of the decade to up to 27.1% (9.9% in terms of LCOE) once all robotic innovations have been realised and an availability increase of up to 1.07% and up to 1.87% respectively.

For a floating wind farm, the results range from up to 18.8% in OPEX reduction (3.9% in terms of LCOE) by the end of 2040 and up to 25.8% (5.9% in terms of LCOE) once all robotic innovations have been realised and an availability increase of up to 1.18% and up to 1.71% respectively.

As the UK offshore wind market matures, this report will enable an understanding of the robotics landscape for offshore wind O&M. It will allow wind farm operators, original equipment manufacturers (OEMs), technology providers and researchers to better understand potential robotic applications. Additionally, the model inputs and outputs produced in this study can be used by those involved in the offshore wind sector for future cost modelling activities.

1 INTRODUCTION

The Offshore Wind Innovation Hub (OWIH) has published a series of technology roadmaps and industry insights that highlight the key challenges and priority innovation areas for the offshore wind industry. A recent OWIH report on the operations and maintenance (O&M) cost drivers [1] identified that the use of autonomous systems and robotics are expected to play a significant role in the reduction of operational costs for inspection and maintenance campaigns. The purpose of this study is to dive deeper into the robotics landscape for O&M and quantify the impact that robotics will have in offshore wind farms in the next 5-30 years, while realising how operations will look like in the future.

This study was led by Xodus and supported by the Offshore Robotics for the Certification of Assets (ORCA) Hub and the Offshore Renewable Energy Catapult (ORE Catapult). The study was 50/50 funded by the Offshore Wind Innovation Hub and the respective organisations.

1.1 The project

Robotic applications are expected to revolutionise the way that operations are currently undertaken, by automating processes, removing humans from dangerous and hazardous environments, improving the way that certain tasks are performed, offering repeatability of actions and contributing to remote and more accurate monitoring of engineering assets. One of the many industries where robotics is expected to make a difference in is offshore wind, which is currently driven by demanding cost of energy targets, awarded by competitive auctions. Robotic applications are expected to contribute to the cost reduction targets, by removing humans from dangerous and hazardous environments and providing quicker and more accurate inspection and repair campaigns.

However, one of the many uncertainties that the offshore wind industry is currently facing is the ability to quantify the impact of robotics. There are many different technologies and applications of robotics in the offshore industry, research is still ongoing with novel robots, analytics and software applications being developed in order to support the assets throughout their lifetime.

Thus, this project aims to quantify the impact of the benefits that robots will offer to new and existing offshore wind farm projects. This work initially developed an expert elicitation methodology, by identifying the uncertainties and selecting the right experts to be interviewed or surveyed. It then created a technology roadmap, taking into consideration the different use cases where robots can support and the different technology penetration rates. Finally, a robotics cost model was developed in order to present all the different scenarios and the associated costs. Xodus and ORE Catapult have run their internal cost models in parallel for greater precision and accuracy in the results.

1.1.1 Work streams

The following work streams were included in the project in order to meet the project aims and objectives:

Interview Framework; an initial interview framework was created, targeting a range of stakeholders, from technology developers and wind farm operators and original equipment manufacturers (OEMs) to researchers.

Expert Engagement; an expert engagement methodology was generated, aiming to have good representation from each stakeholder group.

Technology Roadmap; the roadmap was created as a result of the interview findings and it included a range of answers for all stakeholder groups, grouped in short-, medium- and long-term robotics landscape.

Cost modelling; using the quantitative outputs from the stakeholder engagement, two cost models were used in order to quantify the potential savings of robotic applications and present the results in terms of the change in availability, operational expenditure (OPEX) and levelized cost of energy (LCOE).

1.1.2 Assumptions and Exclusions

This study is focusing on the review of existing and under development robotic applications. The term robotics in this study considers any aerial, subsea or crawler devices that are remotely controlled or demonstrate semi or full-autonomy and are being used for either inspection or maintenance operations. This includes but it is not limited to remotely operated underwater vehicles (ROVs), autonomous underwater vehicles (AUVs), unmanned surface vessels (USVs), autonomous surface vessels (ASVs), unmanned aircraft systems (UAS), any types of drones, robotic arms, and manipulation devices.

Although referenced, this study does not cover any advancements in the fields of sensors (cameras, non-destructive testing (NDT) equipment, etc.), communication systems, internet of things (IoT) and data management and analytics platforms. However, any advancements and limitations of those systems are considered as enablers and/ or barriers for the application of robotics in offshore wind.

Moreover, during the cost modelling exercise, there has been a focus on only capturing the improvements that robots can offer with regards to cost reduction and availability increase. Any other improvement in the wind farms, such as reliability improvements of the wind farm components, efficiencies that can be gained from clustered projects and sharing of resources are not captured in this study.

As indicated in the introductory note, this report is mainly focusing on the O&M phase of the wind farm and not on any robotics applications related to the project development and construction phases of a wind farm. However, information on the use of robotics during the construction and development phase of a wind farm is captured through some of the interview questions and provides a link to the O&M work that is captured in this study.

1.2 Disclaimer

Please note that the views presented in this report are aggregated responses from the stakeholder engagement or any resultant independent analysis from the findings and do not necessarily represent the views of the authors, unless otherwise specified.

Please also note that while the information contained in this report has been prepared and collated in good faith, Xodus and the supporting partners makes no representation or warranty (express or implied) as to the accuracy or completeness of the information contained herein nor shall be liable for any loss or damage resultant from reliance on same.

Offshore Wind Innovation Hub

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ROBOTICS

In the growing offshore wind energy sector, there is a continual drive toward cost reduction and improved safety in operations and maintenance (O&M) activities. Both of these driving factors creates an opportunity for implementing robotics and autonomous systems.

The cost of offshore wind has fallen dramatically in the past few years. For example, the third UK auction round (2019) for UK offshore wind farms produced the lowest strike prices of £39.65/MWh (2012 prices), which is comparable to the wholesale cost of electricity [2] (see Figure 2-1).

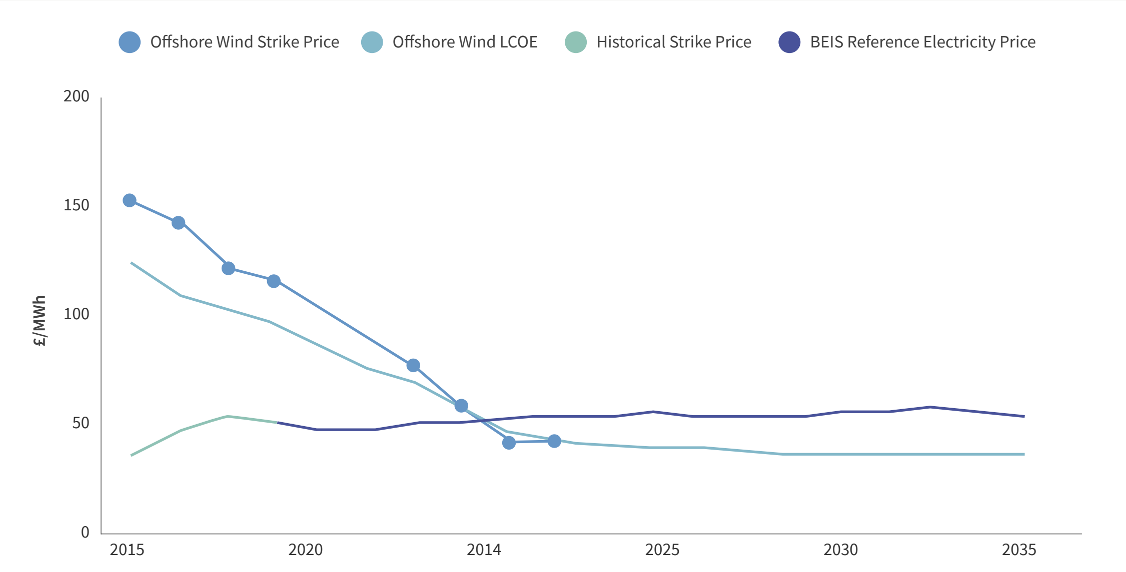

Figure 2-1: Offshore wind and electricity market prices, 2012 real terms (Source: ORE Catapult)

O&M activities typically contribute between 15% and 35% of the lifetime cost of an offshore wind farm [3]. For a 1GW reference wind farm, for example, it was estimated that O&M made up 28.2% of the lifetime cost [4]. The operational cost of wind farms also includes turbine downtime; periods when no power is generated due to ongoing maintenance or having to wait for suitable weather conditions before repairs can be undertaken. Minimising turbine downtime by speeding up response times and task durations is becoming a focal point as the size of offshore wind turbines increases and brings a higher cost (i.e. lost revenue) in periods of downtime (per turbine). There is a clear opportunity for innovations such as robotics to reduce these O&M costs, including turbine downtime, and therefore reduce the LCOE of offshore wind farms even further.

Working in the offshore environment contains an inherent degree of Health and Safety (H&S) risk for personnel. Statistics from G+, the Global Offshore Wind Health and Safety Organisation, show that 72.6% of all high potential incidents in 2019 occurred offshore, on turbines or on vessels [5] (Figure 2-2). A more detailed breakdown of these incidents in shown in Figure 2-3 [6]. This highlights the opportunity for robotics to reduce the number of person-hours spent offshore in high-risk environments and therefore reduce overall H&S risk. For example, the significant number of high potential incidents from working at height could be reduced by replacing the traditional rope-access methods on some O&M tasks with blade inspection robots. Measures like this can play an important part in improving the overall H&S record of the offshore wind industry.

Considering that the global offshore wind capacity is expected to increase almost ten-fold by 2030, to 228GW and to 1TW by 2050 [7], the implementation and potential cost savings can have a huge impact to the offshore wind industry and the energy sector as a whole.

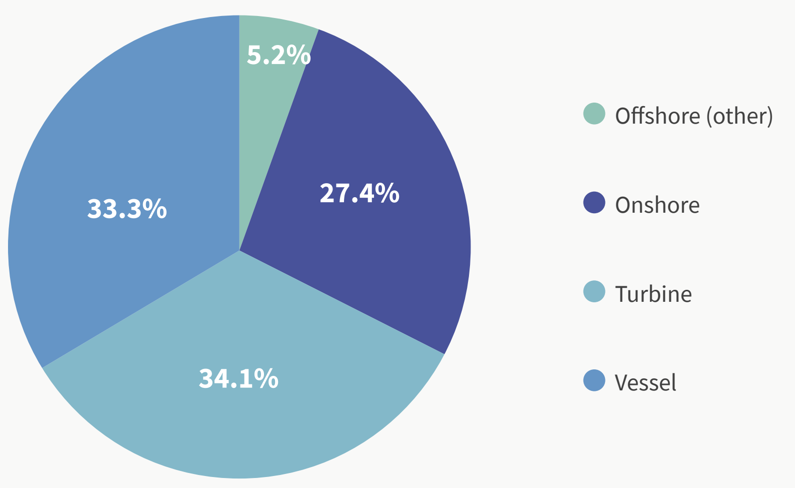

Figure 2-2: Offshore wind high potential incident breakdown, 2019 [5]

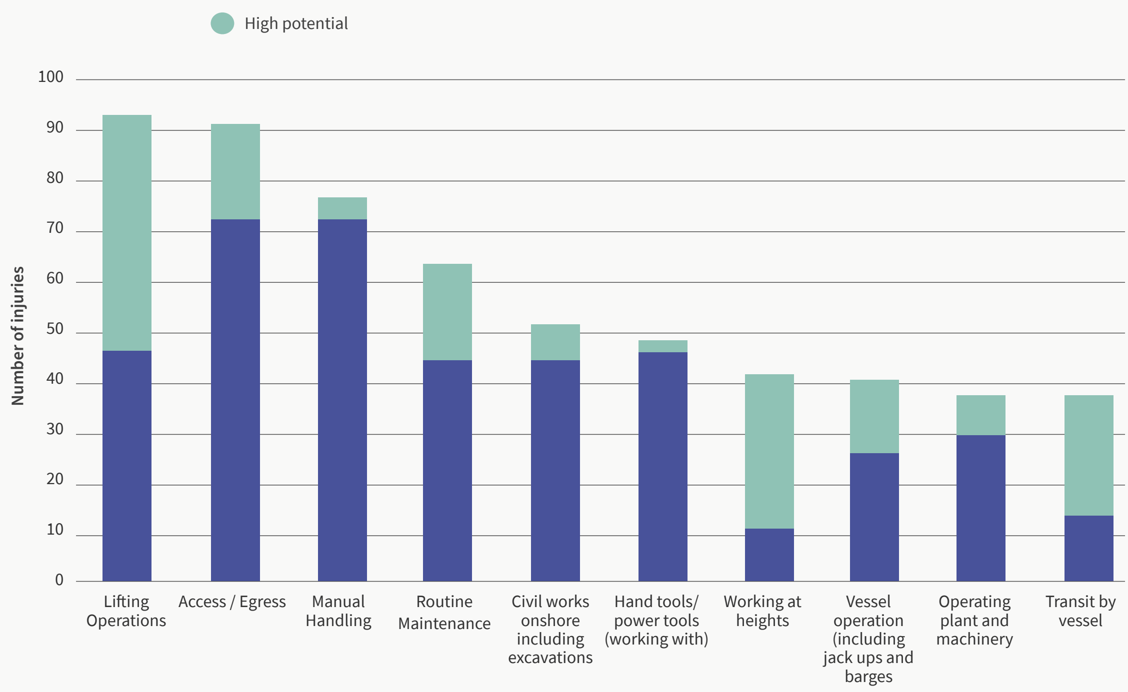

Figure 2-3: Top 10 work processes by number of incidents 2019 [6]

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METHODOLOGY

The methodology followed in this study is shown in Figure 3-1. An overview of the methodology and how the different elements of this study are linked together is presented in this section, with more detail on the specific contents outlined in the following sections.

The work began with the aim of identifying the stakeholder groups and to make sure that a representative sample from each stakeholder group would be interviewed in order to capture all views on the different topics, as well to identify all the success stories and opportunities for improvements for the robotics industry. Having the stakeholder groups in mind, the questionnaire was then developed. To make the data collection phase as efficient as possible, a generic questionnaire was designed that could be used with all interviewees. The engagement with the experts commenced and 22 in-depth semi-structured interviews were conducted in a period of around 9 weeks. The data from the interviews was then collected and analysed to help produce the roadmap, the different cost modelling scenarios, and cost modelling inputs. Finally, once the inputs and scenarios were confirmed, the Xodus and ORE Catapult cost models were used to define the final OPEX cost reduction potential of robotics, the availability increase, as well as the expected final impact on the LCOE.

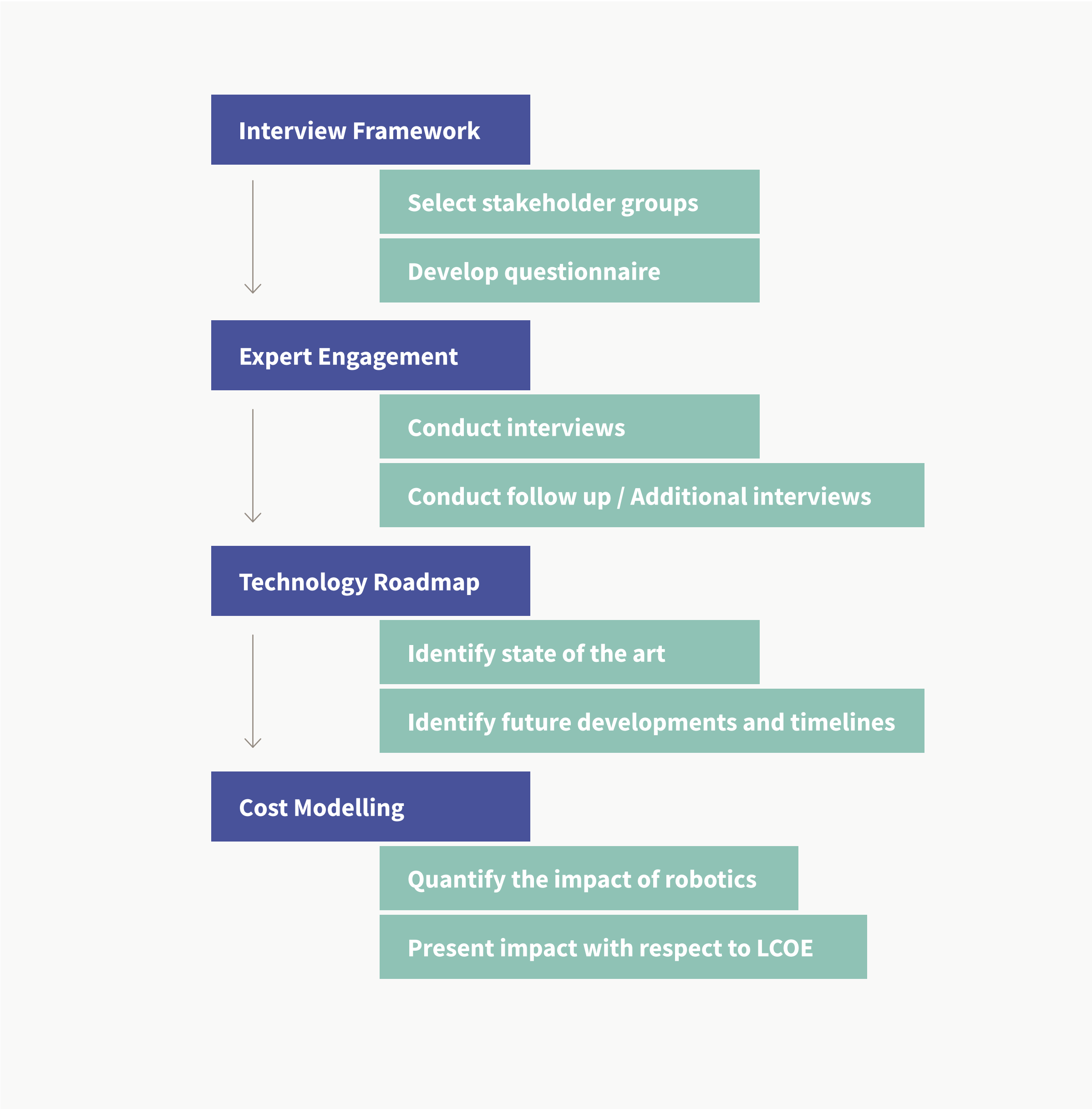

Figure 3-1: Methodology workflow

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STAKEHOLDER ENGAGEMENT

4.1 Stakeholder Groups

To get a full understanding of the current and future state of robotics relevant to offshore wind, experts were engaged from across the supply chain and academia, considering marine, ground, and aerial robotic platforms. This ensured a full and balanced view was elicited.

The stakeholders came from the following groups:

- **Research and Academia:** to capture the cutting-edge research, potential work that could be commercialised in the next 5-10 years, as well as learning from other industries (such as oil and gas).
- **Robotic Technology Developers:** to include the state-of-the-art developments, any upcoming developments from leading and up and coming robotics applications and to also address the challenges that they are facing.
- **Robotic Service Providers:** to address the challenges with using and providing services with robotic devices, understand what is considered state-of-the-art in the field, understand what future solutions would be needed from their perspective, as well as learning from other industries (such as oil and gas).
- **Wind Farm Owners/ Operators and OEMs:** to capture the state-of-the-art application that are being used in offshore wind farms, as well as the challenges with using them from an operational perspective and the limitations on what can and cannot be deployed.

The stakeholder supply chain split is shown in Figure 4-1, where;

- **35%** of the interviewees represented research, academia and innovation centres, with specialisations in autonomous robot planning, control and navigation, sensing, modular robotics, aerial drones, manipulation, subsea autonomy, self-certification, verification and validation of autonomy, and human-robot interaction;
- **31%** technology developers with a range of aerial technology, marine developers, as well as turbine crawler developers;
- **19%** robotic service providers and consultants from a range of aerial and marine industries; and
- **15%** wind farm owners and OEMs, with experience in a range of robotic applications from aerial to subsea.

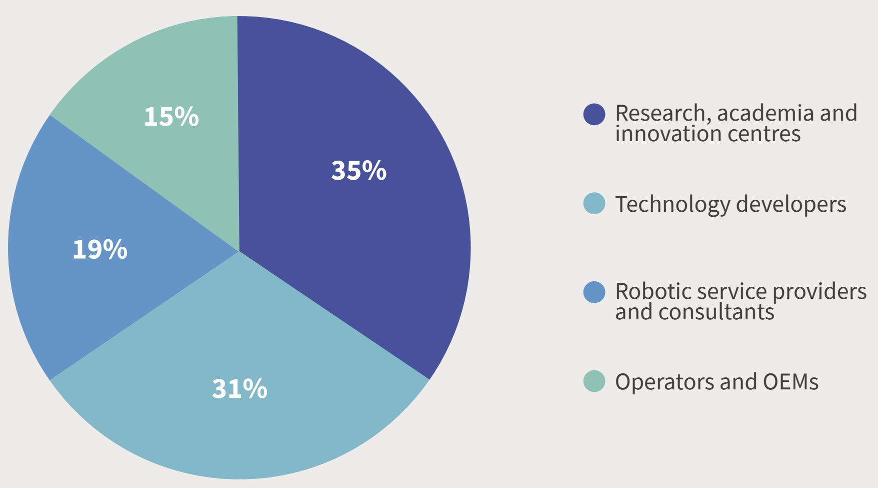

Figure 4-1: Stakeholder supply chain split for interviews

22 interviews were conducted across the above supply chain split. Three companies were classed as both a marine technology developer and robotic service provider. One company was classed as both an aerial technology developer and robotic service provider.

Approximately 35% of interviews focused on cutting edge research while the remaining 65% focused on practitioners to ensure that both new developments as well as the state-of-the-art was captured. As stated above, there was a representative sample from each stakeholder group (and an even split between research disciplines in the research community) to make sure that all opinions were captured. Two follow up interviews were required to ensure the stakeholder expert opinion was captured appropriately.

4.2 Question Framework

The question set was divided into two sections. The first section was a set of fourteen predominantly qualitative questions. The interviewee first introduced themselves and their organisation to set context. The interview questions then asked about their opinion on the general state of robotics, moving into where they see it in the future. It then narrowed in on the specifics of the technology the interviewee was involved in, if appropriate. The second section was a quantitative table aimed at eliciting specific numbers to provide an understanding of the effects on cost, time saved, labour, risks, efficiencies enabled, and a timeframe of impact. As it was a semi-structured interview format, additional questions were asked on occasion if a particular comment from the interviewee was deemed relevant to the report and worth expanding on.

A summary of the questions that were asked is included below:

- **Questions 1-2:** General information on the interviewee and their organisation and/or department
- **Questions 3-5:** Current strengths, challenges, and barriers for the deployment of robotics in offshore wind applications
- **Questions 6-8:** Understanding the future robotic landscape and limitations, as viewed by the different stakeholders
- **Questions 9-13:** Tools and techniques that are applied by the individual stakeholders, their benefits, timelines and importance
- **Question 14:** Any additional comments that the participant might want to add.
- **Question 15:** A quantitative table assessing the effect on cost, labour, time saved, risk, efficiencies and time realised for a range of categories (depending on the tools and/or services of the interviewees organisation). The aggregated list of inputs to this table is shown in Table 72.

The link between the questions and the different parts of this work are shown in Figure 4-2.

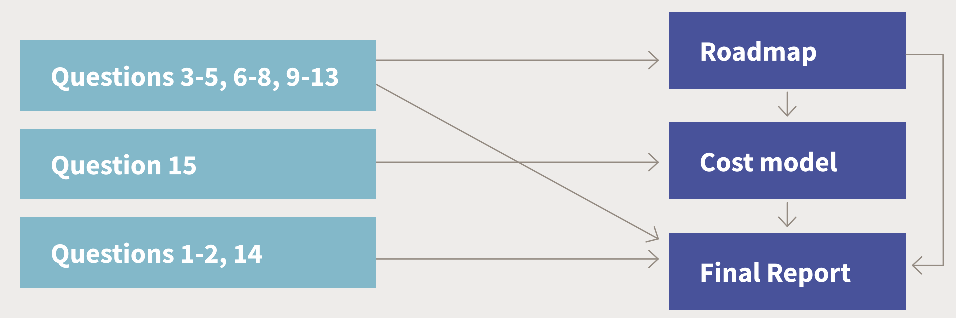

Figure 4-2: Interview questions and their links to the different project phases

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STAKEHOLDER FINDINGS

This section summarises the findings of the stakeholder engagement exercise. The views presented in this section, represent those of the interviewees and not the authors.

There is a lot of commonality across those that provided input into the report about the benefits and value robotics could provide the offshore wind sector which align with those stated in Section 2. One noted driver for using robots for offshore wind operations is for improving safety. Robots that can carry out tasks that remove people from dangerous offshore working environments such as diving operations, confined space entry and working at height are seen as short-to-medium term developments. Longer-term, the almost complete removal of people from the offshore environment is expected, with people supervising, monitoring, and directing robots that work offshore autonomously and independently from the safety of remote operation centres onshore.

Reducing cost is another driver for organisations considering the use of robots for operations. Anecdotally, the use of robotics for operations is expected to reduce cost by removing or reducing people from offshore operations, remove or reduce the number of vessel trips required to transport people offshore, improve operating weather windows, enable inspections, operational decisions, maintenance, and repairs to happen quicker and reduce the amount of turbine downtime. The industry is not currently in a position to realise these benefits in full but robotic developments are starting to demonstrate significant value and the areas where improvements are needed have been highlighted so the sector can continue to address them.

5.1 Current and Future State-of-the-Art

For the purposes of this report, we consider the term robotics to include any aerial, subsea or crawler devices that are remotely controlled or demonstrate semi or full-autonomy and are being used for either inspection or maintenance operations. This includes but it is not limited to ROVs, AUVs, USVs, UASs any types of drones, robotic arms, and manipulation devices. Below are examples and success stories shared by the wide range of interviewees.

5.1.1 ROVs

ROVs are considered robust, reliable and can carry out most tasks divers can. The majority of the work required of them in the offshore wind sector is to carry out tasks such as inspection of scour protection, cables and cable exit points, cathodic protection, and general inspection of boat landings and turbine foundations for biofouling and corrosion. Their use in offshore wind was a natural progression from the oil and gas industry, where they have been common practice for subsea operations since the 1980s. The platforms commonly used operationally in offshore wind today are seeing small elements of automation integrated but are still generally tethered systems remotely controlled by people in support vessels on the surface.

Recent developments in this area have seen the introduction of hybrid USVs combined with electric remotely operated vehicles, or eROVs. eROVs do not need hydraulic systems and are easier to deploy from surface vessels, which in turn allows the vessels to become unmanned. Because space for personnel is not required on unmanned vessels, they can be designed more efficiently so they are smaller and therefore more fuel efficient, helping reduce carbon emissions. Further value will be achieved from this multimodal robot offering because combined USV-eROV platforms can be controlled from onshore remote operation centres enabling remote control of operations from the safety of land. Improvements in communication between onshore offices and offshore wind farms are still required to fully realise this potential. However, with the deployment of several thousand low-earth orbit satellites providing high-speed satellite broadband with low latency data transfer that is taking place over the next ten years [7], [8], remote long-range connectivity is expected to improve significantly in the short to medium term and will support this advancement. The development of combined USV-eROV platforms will play a substantial role in the safety benefit of removing people from offshore operations. While these systems are currently being introduced, they are not common practice for offshore wind operations.

5.1.2 AUVs

Autonomy is not common practice operationally, although aspects of it are being introduced and will continue to be over the next five years. Full autonomous systems are expected to be operational at different levels over the next 5-20 years.

Autonomous Underwater Vehicles (AUVs) are currently used occasionally for bathymetric surveys and can provide substantial reductions in operational time, and therefore cost. In one example provided, a traditional bathymetric survey using a survey vessel took approximately one and a half weeks for a site, while the survey using an AUV covered 60% of the same site in one day and the support vessel was able to carry out other operations while the AUV carried out its survey. The compromise, however, was the quality of the survey data from the AUV, which did not meet the same standard as the traditional method. Significant work is being carried out both in the academic world and within private sector research and development departments to make marine operations reach that full autonomy vision. Work in autonomous mission planning, navigation, localisation, positioning, mapping, launch and recovery/docking, feature detection, and manipulation is in varying degrees of development.

The technology is building towards a capability that will enable resident or semi-resident autonomous systems where subsea robots are permanently or semi-permanently based at offshore sites. The capability will see different styles of AUVs based in subsea docks for long periods, providing inspection, repair, and maintenance (IRM) capability as and when required from the direction of people based in the previously mentioned remote operation centres. AUV agnostic, standardised battery charging and data download connections that are in development will ensure power is available to recharge AUV batteries and data that has been processed by the system on site is transmitted to shore and provides actionable insight. This capability is currently being developed in the oil and gas industry and considered likely to transfer to the offshore wind sector in the future given some of the supply chain in this domain work across both sectors.

5.1.3 UASs

The use of Unmanned Aerial Vehicles for visual inspection is now common practice in the offshore wind sector. Its adoption is seen as a role model for the wider potential robotics can bring to offshore wind. Previously, inspection operations required a team of three rope access technicians to visually inspect the three blades on a wind turbine. The average time to complete a wind farm inspection was approximately two weeks for a 25-30 turbine offshore wind farm, excluding any weather delays. Currently, several companies are providing UAS inspections of blades. The capability requires a pilot who controls the UAS and a support technician who maintains visual contact with the robot and warns the pilot of any potential hazards. This has reduced typical blade inspections to approximately one week for an averaged sized wind farm. Like that of marine robotics today, aspects of automation and autonomy have started to be integrated into elements of the operation. Some providers are capable of take-off and landing autonomously from the Service Operation Vessel (SOV) as well as automated inspection of the blades. This has reduced the time taken for blade inspections of a full wind farm to approximately one day [9]. While this is not currently common practice, the technology is ready.

Several organisations are also investigating adding UASs to USVs so aerial robots can launch from an unmanned vessel with no human piloting required on site for either transport to site or for the inspection operation. Human monitoring and control of both systems will take place at the onshore remote operation centres. This vision may be taken a step further by combining the previously mentioned USV-eROV platforms with autonomous or Beyond Visual Line of Sight (BVLOS) onshore remotely piloted UASs, providing a multimodal capability for dual operations that take place both above and below the waterline simultaneously.

Research is being carried out on autonomous UAS manipulation. This work is investigating how UASs can physically interact with infrastructure safely and reliably in order to carry out more complex tasks such as contact-based Non-Destructive Testing (NDT) with a suitable sensor payload, lightning protection system (LPS) system checks, drain hole cleaning, and leading-edge protection (LEP) repair and reapplication.

While there are promising crawler robotic platforms in development, none are currently used operationally in offshore wind. Expected to be commercially ready in the next 2-3 years, these sensor agnostic crawler systems will autonomously navigate around areas of interest, whether on the blade or the turbine tower. Similar to the vision for UAS manipulation, depending on the sensor payload installed for the operation, they hope to provide a robotic solution for comprehensive visual inspection, contact based NDE, LPS checks and LEP repair and reapplication.

Like with marine operations, the vision for aerial operations is to have resident systems, where robotic platforms are permanently or semi-permanently based in a protected environment on the turbine or substation. These autonomous platforms will be available to carry out tasks as required and do so either upon instruction from people in remote operation centres or as the platforms themselves believe it is necessary. Different sensor and tool payloads will be housed on each turbine or 'hub' turbines that UASs can pick up depending on the activity to be carried out. This approach moves away from the traditional transactional exchange of service companies providing their service when requested by the wind farm operator and delivering a report showing results upon completion. Instead, operations are not carried out as part of a fixed work plan but occur at any point they are deemed necessary and when the suitable operating conditions allow the robots to work. Offshore tasks will be carried out continuously with alerts raised when the robots detect the systems are at risk.

5.1.4 Resident systems

The resident system approach for subsea, turbine crawler and aerial robots will significantly increase the weather windows operations can be carried out in because the platforms will be on-site ready to work whenever weather windows permit. It will also dramatically reduce transit costs as people will only be required for operations that are considered too complex or demanding of the robots, or the robots themselves require human intervention. This supports the safety benefit of reducing the number of people working offshore while also having a positive impact on both cost and CO_2 emission reductions associated with the movement of people to and from offshore sites. This proactive approach to O&M operations will provide much more data about the assets. Artificial Intelligence (AI) will filter these data and process only those relevant to provide actionable insights about the health of the assets. A term coined as "passive vigilance", where only necessary data is collected and used to enable systems and people to act only when it is needed but also in a manner that enables optimised planning of maintenance and repairs. It is expected this will significantly reduce the amount of turbine downtime.

5.2 Current Limitations and Opportunities for Growth

While the above strengths focus largely on the technology readiness of robots now and in the future, the areas that are deemed weak, in need of improvement or preventing the full adoption of robotics include aspects such as their economic benefit, regulation, standardisation, the supply chain and social factors, as well as technological readiness.

The questions being asked are:

- What is technologically ready?
- What level of robotics and autonomy are people willing to accept?
- What cost benefit is there in using them?
- Are regulation and standards in place for them?
- Are the correct resources and organisations in place to support their development and adoption?

5.2.1 Ranking of barriers

The main barriers preventing the adoption of robotics in offshore wind are shown in Figure 5-1, as identified by the interviewees in terms of importance (with 1 being the biggest one and 6 the lowest one). Please note that some interviewees did not rank all the listed barriers, so there are less than 22 answers for each barrier. Another barrier that was listed by one of the participants – the safety of BVLOS operations - was not part of the original list.

The findings show that the economic benefit is considered the biggest barrier with 32% of the interviewees ranking it as the number 1 barrier and 22% as number 2, followed by regulation, technology readiness and funding. Regulation was also ranked by 18% of the interviewees as number 6 and 14% of participants mentioned that it is not a barrier for them. Resourcing comes last, with 55% of the interviewees ranking it as 5 or 6 and 27% not listing it as a barrier at all. Social factors had mixed rankings, with 41% of the participants ranking it in the top 3 barriers, 36% as 4, 5 or 6 and the remaining 23% claiming that in their opinion, it is not considered a barrier.

Within the stakeholder groups, there was a difference in the rankings:

- **44% of the interviewees from research and academia believe that the biggest barriers are the economic benefit**, followed by regulation and technology readiness, where 63% of the responses had those two barriers ranked in the top 3.
- **Technology and service providers stated that the biggest barrier is the lack of funding**, with 75% of the responses having it in the top 3 spots, followed by the economic benefit and the technology readiness, both at 63%.
- **Operators / OEMs believe that the biggest barriers are the economic benefit**, followed by regulation and technology readiness.

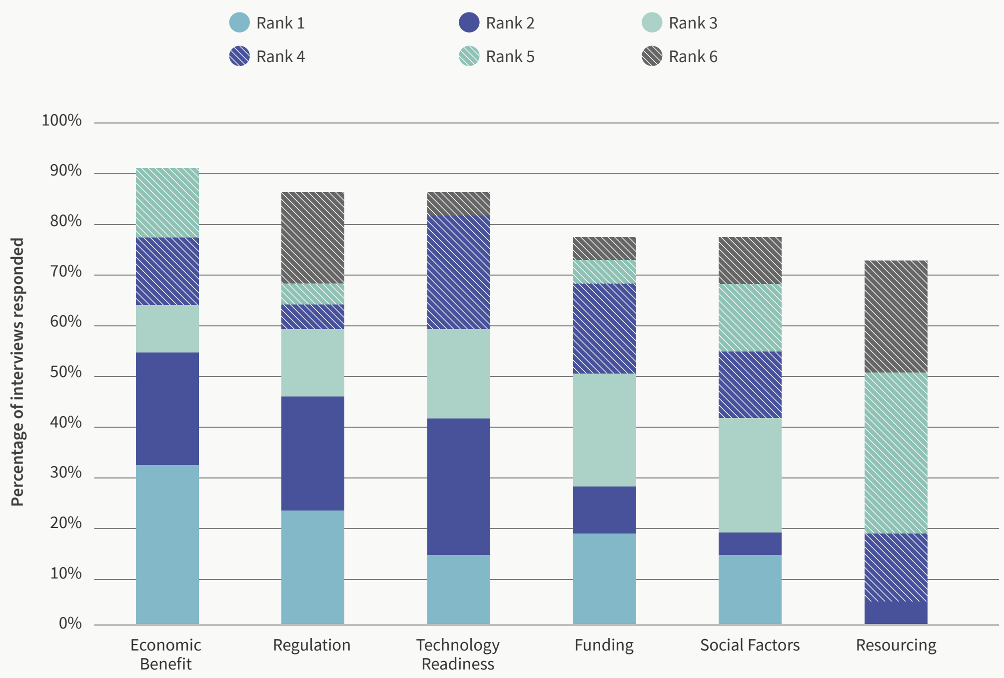

Figure 5-1: Ranking of barriers preventing the adoption of robotics in offshore wind

5.3 Technological limitation

While the interviewees' opinions on the current and future state-of-the-art is mentioned above, there are advances in technology that are still required to realise the visions mentioned. Inspection tasks are currently carried out well by robotic systems, but very little intervention and manipulation is currently being done in offshore wind. Complex tasks that require the dexterity of human hands are still a challenge for robots in dynamic environments such as offshore. While successes have been made by academia in lab-based experiments or controlled demonstrations, the reality of robots having this capability is expected to be over 5 years away. A robot's ability to understand context still also requires further development. While AI is getting better at tasks such as identifying features and objects, and this capability is starting to appear operationally, robots are not currently able to understand the contextual relevance of the objects they detect within their environment to the same level people can. Related to both a robot's ability to carry out intervention tasks and understand the context with which it is working in is linked to a robot's current ability to only carry out a limited number of tasks. There are a great number of activities involved in a full O&M programme, so adaptive robots that are multifunctional will reduce the number of different robots required to complete the full suite of activities. This capability is still to be realised.

There are several improvements with robots at a component, functional and capability level that are deemed necessary before the future state-of-the-art can be achieved. This includes:

- Improvements to robot friendly sensors. That is, sensors that are small, lightweight, can integrate with a robot's operating system and capture high quality data.
- The performance of batteries or improvements in robot power consumption are considered necessary to improve the current longevity of operations carried out by robots.
- Improvements in specific functionality such as an ROVs hover capability. ROVs have largely been developed for work in the oil and gas industry where activities typically take place in deeper water and ocean currents are not such an issue. For fixed bottom offshore wind farms that are closer to shore and in shallower waters, strong hover capabilities are necessary for close visual inspection and manipulation tasks, but current ROV capabilities do not perform well in the currents experienced at these water depths.
- Improvements in the lift capacity of UASs is required so multiple sensor payloads can be integrated to give the platform either more functionality or combine data from the sensors for improved inspections. The ability for UASs to lift tools and consumables to people on rope access carrying out repairs is also seen as a use case for the platforms that will make small improvements to operational efficiency. Lastly, the ability for UASs to transport robots such as the previously mentioned crawlers from either the turbine work platform, support vessel or USV is being developed but is not currently realised operationally.

There are improvements that could be made to the interface with the turbine that would make them more robot friendly. The challenges faced by robot service providers include weather proofing, power, and data. When weather windows close during operations, there needs to be a safe place to shelter to protect the UAS. Additionally, ensuring there is enough power for the robot to carry out its mission is currently a major consideration for robot providers. Finally, to transmit data collected during the missions to the remote operations centres, there needs to be the necessary communication infrastructure made available. By providing these capabilities at the turbine, the step to residency becomes a little closer. All these provisions can be provided using technology and resources available today, but the sector must work together to make them a reality.

Data is seen as a central player in the conversation about robotics for offshore wind. A key function of robots is as a method of collecting data about the asset. It is widely considered that the most value out of collecting lots of data will be when it is fused together to provide a holistic, helicopter few of the health of the asset. Similarly, being able to pool the data from as many assets as possible in a shared sector "data lake" – a secure and anonymous database of all turbine data – will provide the industry greater insight into how to best manage individual assets. This collective data sharing will allow operators to run their wind farms much more efficiently, ultimately reducing downtime, improving production uptime and lower LCOE. However, there is currently a hesitation to openly share data due to concerns about privacy. While this is an important consideration that needs to be managed, it is felt that the industry as a whole has more to gain by taking a collaborative approach with asset data.

5.4 The business opportunity for technology developers

In addition to the technological challenges facing the widespread use of robotics for the offshore wind sector, further work is also required to better understand the economic benefit they will bring. In order for wind farm operators to justify the use of new technology or changing the current operational workflow, there needs to be a strong business case presented. While this business case largely considers the commercial benefits, methods that provide significant health and safety benefits are also taken into consideration. It is felt that these benefits are not currently presented well enough to wind farm operators to justify their use to their internal stakeholders. Although the robot may be technologically capable of carrying out a specific task to a similar standard or better than a person, its ability to make the task cheaper is often not communicated well enough. Similarly, the specific applications for some developments are not always made clear.

From a developer perspective, the time, cost, and risk required to take an idea for a new technology and develop it through to a commercial product is high and considered a major hurdle. Currently, the use of technology is transactional, where a technology developer takes the time and risk to get a product to a usable point, at which time a wind farm operator buys it as a service. When a new technology or methodology for working is proposed, often the established contractual, commercial, and procedural setups embedded in the wind farm operators prevent truly innovative approaches from being integrated into working practices. Additionally, because the environment that the technology is to be used in is so remote and inaccessible, demonstrating that the system is both functionally capable and safe for its intended application is more challenging than developing technology for other sectors. While test facilities such as the Offshore Renewable Energy Catapult's site at Blyth and Levenmouth are invaluable for product testing and development, the leap from this environment to a product that is fully operational in an offshore setting is still considerable. More investment, support, and an open mind from end users at an early stage of an innovative solution is deemed necessary to help accelerate the development of technology, reduce the risk on the developer, and alleviate some of the cost burden.

5.5 Regulation

Regulation and the relationship with regulators and other public authorities is seen as an area that could be improved to help the use and adoption of robotics in offshore wind. The speed at which discussions currently proceed only allows for marginal, incremental developments to work their way into operations. **The speed at which robotic technology is advancing requires organisations that support the offshore wind sector to move at a similar pace so those advances can have a profound impact.** For example, the technology for remotely piloted BVLOS UASs is available and demonstrations of the capability have taken place but in order to carry out a BVLOS operation, strict criteria and alignment with others using the airspace must be met, which is important but takes time. It is felt the Civil Aviation Authority (CAA) is set up to cater for large aircraft that last for approximately 30 years rather than small, agile, and nimble platforms like UASs that are designed to last for 5-10 years. The two cannot be assessed using the same processes. Satisfying risk assessments and regulations that were not designed or written for the new systems and platforms can slow the process of demonstrating and introducing robotics into the sector. A similar view is held for the marine environment. There are multiple stakeholders who need to be made aware that new methods of working and systems are being introduced, such as unmanned vessels using the water. For example, without proper communication, other seafarers may be alarmed when encountering such systems at sea. Building relationships with and convincing these stakeholders takes time and introduces an additional challenge to those technology developers with something progressive to offer but new to the sector.

An additional view held related to regulation involves considering scenarios where multimodal systems are in operation. That is, when a USV is used as a launch platform for UASs, and ROVs or AUVs while they carry out operations in tandem. This type of scenario is expected to be realised in the short to medium term given there are solutions being developed and trialled today and technological capabilities are not seen as the barriers preventing their operation. However, as you incorporate aerial and marine based robotics, and cross boundaries between environments, there is a risk that confusion or conflict arises around which safety and quality standards and regulations are applicable and are those standards and regulations adequate to cover that type of joint operation. Suitable integration of regulations, and safety and quality standards should be addressed now in preparation for that capability being ready for deployment otherwise it will face a bottleneck that slows down the value multimodal systems can provide to the offshore wind sector. In addressing this it is important that regulators such as the CAA and the Maritime and Coastguard Agency (MCA), and standards bodies such as the British Standards Institution (BSI), International Organisation for Standardisation (ISO) and Eurocae, work collaboratively so updates are synchronised and there is no overlap.

5.6 Standardisation

Common standards and standardisation is considered an area where there is an opportunity for improvement that will support the adoption of robotics in offshore wind, and service robotics more generally. Without well-defined industry standards, systems and connectors, robots, parts, and components become bespoke. This may lead to robots becoming very technical systems, which will require expensive bespoke parts and components, and very technical teams to fix and repair them. There are currently very few who are sufficiently trained in robotics. Many of them are PhD educated and trained. For the use of robotics to become widespread, it will not be feasible to have only highly educated individuals capable of working on robotics. To use an analogy from the automotive sector, there are a few well educated car designers and a large network of skilled independent garages keeping built cars on the road safely. The same is considered necessary for robots. **By agreeing on a standard approach to designing, building, and certifying platforms, the door is opened for a wider range of robot providers and interoperability and connectivity between platforms and sensors.** It also allows for robot mechanics to emerge and provide repair and maintenance services to a wide range of robotic systems. This would reduce the reliance on robot OEM only repairs, which could introduce a bottleneck when trying to put defective robots back into service. This approach would also encourage a competitive robot servicing market that will reduce robot repair costs.

5.7 Collaboration

It is widely believed that to support the adoption of robotics in offshore wind, a central supply chain interface is necessary to bring all the stakeholders together. Throughout the interview process, it was identified that there is scope for improved communication between the technology providers and the end users. The former indicated that more input is required by the wind farm operators and OEMs in order to test their devices and receive operational feedback and the latter state that a compelling business case needs to be demonstrated in order to trust and deploy new robotic applications.

An organisation with a robotics-specific focus that brings together technology developers, service providers and wind farm owners to form an alliance that feeds the whole O&M process into a collaborative ecosystem is considered a valuable addition to the supply chain. This independent body could collate and disseminate end user challenges, encourage, and facilitate communication across the supply chain, promote non-competitive joint developments, share anonymised lessons learned, organize open robot demonstration days, and generally provide a collaborative, top-down, holistic view that invites connected innovation.

5.8 Social factors

The final area that is deemed important to consider when understanding the use of robotics in the offshore wind sector is the social aspect. That is, the psychological readiness of the sector to adopt and use robots. This area is not unique to offshore wind. In order for the value of robotics to be fully realised, users must have confidence in their capability, safety and reliability. They must trust that the platform can do the tasks that the providers say they can do. Understandably, there is a tentative and apprehensive mindset about using robots around high-value assets such as wind turbines. This is especially the case when the human is largely removed from direct control of the robot and becomes a supervisor as opposed to an operator, which is the case for autonomous systems. This risk aversion often means that users prefer to be technology followers rather than first movers. This creates a further challenge for robot developers trying to find a company willing to try their technology for the first time, which slows down the development and subsequent adoption of platforms that may provide significant cost and safety benefits. To overcome this, research is being carried out in the ORCA Hub and the UKRI Trustworthy Autonomous Systems (TAS) Programme that looks at understanding human-robot interaction and building trustworthy autonomous systems. This work looks to build strong human-robot collaborative teams and design autonomous robots so that their actions are transparent, developing techniques that provide the user with greater situational awareness about the operation that the robot is carrying out. In turn, this builds greater trust between the human user and the robot.

5.9 Future Value of Robotics

The stakeholders are aligned in their opinion that robots have value to bring to the offshore wind industry. While they are used today, they are largely considered 'dumb' devices that require people situated offshore to control them. Although elements of intelligence and autonomy are being added to these systems, supporting the human operator controlling them, the full value of robotics remains to be realised. Most interviewees agreed that **robot residency** will bring a step-change in cost savings and improvements in safety. It is widely agreed that this capability will bring benefits in the following areas:

- **Weather operating windows:** resident robots will be able to react to openings in weather operating windows much quicker, enabling operations to take place more regularly.
- **Inspections:** being based onsite and able to react quicker to weather operating windows means inspections will be more frequent, taking place when they are required, not when they fit into a pre-planned work programme.
- **Data:** the robots will be able to collect more data, and the data will be more consistent, repeatable and of better-quality, enabling more informed decision making.
- **Maintenance:** less maintenance will be required because better data will inform a proactive maintenance programme that prevents defects from getting too severe. This also enables the robots to carry out the repairs as they are flagged and acted upon before they become too complex for them.
- **Turbine uptime:** more frequent inspections, better knowledge about the health of the assets and less maintenance will result in less turbine downtime and more energy production from each turbine.
- **Reduced time at sea:** as people will not be required onsite to carry out inspections and repairs as often, people will spend significantly less time at sea.
- **Cost:** as people will not be required onsite as often, significant cost savings will be achieved through the reduction in sending manned vessels to sea. Additionally, less maintenance costs will be incurred as a result of proactive maintenance programmes.
- **Safety of operations:** offshore operations will become much safer as less people are required to go offshore.
- **Reduced Co2 emissions:** with less people required offshore and operations largely being carried out remotely, there will be less vessel time required transporting people to site, which will reduce the amount of CO2 emissions.

In order to reach this capability, improvements are needed not just in the technological developments of the robots themselves but also in demonstrating the economic benefit to wind farm operators, in regulation, in the standardisation of robots and components, and social factors related to trust and the adoption of robotics. This multifaceted area requires better collaboration within the supply chain to enable more connected innovation within the offshore wind sector.

6

ROADMAP

Table 6-1 shows the robotics roadmap, as envisioned by the individual stakeholder groups for the next decade, 2030-2040 and 2040 and beyond. It should be noted that the developments expected to be realised within the next 5 year timeframe refer mainly to technologies that have been either showcased and deployed in other sectors, such as oil & gas, or have been used in pilot projects. Moreover, the views presented are from a range of stakeholders that might have had different views in terms of the commercial applications of certain technologies and in which timeframe these could be achieved; in those cases an approach presenting the average cases of the conflicting views was considered.

6.1 Roadmap responses

There was general agreement from all the interviews and the data collected about the future direction of travel for robotics in offshore wind. Details of the future landscape are highlighted below.

2025-2030

Robotic applications will be similar to those currently used today but their capability will be improved iteratively, and inspections will be more frequent. UAS inspections will be common practice as ROV inspections are today.

Aspects of autonomy such as navigation and localisation will increase for individual robotic systems in aerial, surface, and subsea environments. Teleoperated ROV manipulation with the support of vessels will migrate from oil and gas while autonomous manipulation will be demonstrated. Capabilities that will enable resident systems such as auto-docking, battery charging, and data transfer will also be demonstrated. BVLOS demonstrations of remote teleoperation of both UASs and combination USV-ROV platforms will also be shown.

Operations will start to be monitored live by people onshore at remote operation centres. The quantity of data captured will significantly increase and more machine learning (ML) and AI will be used to analyse it. These data will continue to feed digital twins of turbines, as they are today, to support turbine monitoring by people onshore.

As confidence in robots grows, the sector will start to consider how future turbines could be designed to be more robot friendly. However, robots will still be reliant on people, people will still travel offshore for operations and vessels will therefore still be required for logistics and onsite support, including remote control of the platforms, data retrieval and safety.

2030-2040

The next decade is expected to revolutionise the way that operations take place. Much of the innovation being demonstrated today will be realised and new devices and concepts will be demonstrated and tested. Aerial, turbine and subsea surveys and inspections will be carried out by robots as a matter of default. Robots will start to carry out multiple tasks that include inspection as well as minor maintenance and repair. They will also start to be used for activities in the construction and decommissioning phases, as well as for safety applications.

Autonomy will be more common and experience an increasing level of acceptance. Resident systems for UASs, AUVs and crawlers will start to be introduced and USVs and UASs, and USVs and ROVs/AUVs, will start to work and communicate together in tandem. The communication between onshore and offshore sites will have improved to allow more work to be monitored and controlled at onshore remote operation centres. BVLOS operations such as long-term deployment of USV-ROV/AUVs will be common practice.

Turbines that have been designed with robot operations in mind will start to be installed. These turbines will also have embedded sensors for wind farm IoT and full implementation of digital twins for onshore turbine monitoring. This plus the use of AI for operational planning support as standard will enable proactive inspection, maintenance, and repair activities. This optimised planning and the increased use of robots that are less reliant on human control will significantly reduce the amount of people required offshore and the subsequent manned vessels necessary to support them.

2040 and beyond:

This period is expected to be the beginning of the implementation of full field autonomy, starting from the 2040 decade. Full resident system solutions for UAS, AUV and turbine crawlers will be permanently based on the wind farms, with docking and charging systems in place to support this capability. Robots will be able to self-diagnose their own faults and in certain cases self-heal and self-certify.

Most turbines will have been designed to accommodate robots rather than people. ‘Smart’ turbines and robots will work symbiotically so most O&M operations are carried out by robots, with many being able to carry out multiple tasks. Through the significant amount of data being available, optimal planning will be accomplished through a master AI system that will act as a “manager” for all robot activities offshore. Operations will be optimised around weather and seasons, so inspections, maintenance, and repairs are carried out at all non-windy and good weather periods, so turbines are available to produce power during all turbine operating weather windows.

People will largely work onshore, only required offshore for major or unusual turbine maintenance and repairs, the collection of damaged or faulty robots for maintenance and repair, or to work alongside robots on installation and decommissioning activities. Operations involving multiple robots will be monitored and supervised by people in remote operation centres, providing support when required. It is expected that this vision of the future will increase wind farm availability, reduce O&M cost and significantly reduce H&S risk.

6.2 Overcoming the barriers

A range of barriers have been discussed in Section 5.2 and in order for the roadmap predictions to be realized, certain steps need to be taken in order to overcome those barriers.

The UK has taken and continues to take significant strides in addressing the barriers highlighted in this report. Through the government’s Industrial Strategy Challenge Fund (ISCF), the UK has invested significantly in bridging the gap between academia and industry so new technology developments and UK created IP finds its way into the global supply chain as quickly as possible. A large portion of funding has been directed towards creating collaborative academic-industry projects aimed at developing robotics and AI. An example of this is the Offshore Robotics for the Certification of Assets (ORCA) Hub, funded through UK Research and Innovation (UKRI) and managed by the Engineering and Physical Sciences Research Council (EPSRC), and who coauthored this report. The ORCA Hub now involves thirteen UK universities and over 30 industry organisations who are jointly developing robotics, autonomous systems, and artificial intelligence for the offshore sector. Similarly, Innovate UK has funded 26 other offshore focused collaborative academic-industry projects developing robotics, autonomous systems, and artificial intelligence for the offshore sector. This funding has helped make the UK supply chain become a global competitor in developing robotic solutions for the offshore sector, creating, and supporting many small and medium-sized enterprises (SME) robotics companies. Many of the technological and social factor barriers highlighted in this report are being addressed within these projects.

The universities and companies are further supported in their offshore robotic developments by organisations such as the Offshore Renewable Energy (ORE) Catapult – another coauthor of this report, the Digital Catapult, and OGTC. The ORE Catapult and Digital Catapult provide both facilities and expertise to support companies and universities to transition and accelerate their ideas and developments into the market. OGTC provides another avenue of funding and connects technology developers with end users and potential customers. These organisations also support companies to better understand the economic benefit of their technical solutions so they provide viable and competitive products and services.

Additionally, EPSRC has funded several Centre for Doctoral Training (CDT) programmes that are educating and training individuals in areas of expertise related to offshore wind, robotics and autonomous systems. Examples include the Centre for Doctoral Training in Robotics and Autonomous Systems (CDT-RAS), led by Heriot-Wat University and involving The University of Edinburgh, and the Centre for Doctoral Training in Offshore Renewable Energy (IDCORE), led by The University of Edinburgh, alongside University of Exeter, Strathclyde University, and the Scottish Association for Marine Science (SAMS). It is still necessary to address the requirement for lower skilled robot mechanics who will fix and maintain robots once they have been adopted by the sector. However, these CDT programmes will help ensure that the right level of talent and human resources are available to companies to support the offshore wind robotics vision presented in this report.

On the regulatory aspect, the Drones Pathfinder programme was launched by government (run by BEIS in partnership with a range of other key stakeholders) aiming at bringing near commercialisation technology forward and working closely with policy makers and regulators to accelerate legislative feasibility. So far the Pathfinder has focused on key areas such as national infrastructure, security and other areas, although ORE Catapult have been discussing potential for offshore wind to be an area of focus. Moreover, the International Maritime Organisation is assessing existing instruments to see how they might apply to ships with varying degrees of automation, which will inform the strategy of the Maritime and Coastguard Agency in the UK.

ROBOTICS ROADMAP 2025-2030

Figure 6-1: Robotics roadmap for offshore wind applications

Offshore Wind Innovation Hub

ROBOTICS ROADMAP 2030-2040

Demonstration of new 'unimagined' robots

Robot Design

Introduction of hybrid, multi-task robots

Introduction of 'first responder' safety robots

Robot Capability

Introduction of heavy lift UASs in operations for tasks such as tool and robot delivery

Introduction of robots used in construction and decommissioning

Introduction of robot minor maintenance and repair such as blade repair

Improved collaboration between UASs, USVs, ROVs and AUVs for inspection and repair operations

Autonomy

Introduction of singular resident systems

Introduction of robot self-healing and self-certification

Semi-autonomous BVLOS operations 'business as usual'

High-speed onshore-offshore communication

BVLOS

USV-ROV/AUVs used for multi-field long-term survey and inspections

Robot friendly turbines being installed

Turbine Design

'Smart' turbines will support proactive planning of inspection, maintenance, or repairs

Remote operation centres used to monitor multiple robots onsite

AI for operational planning 'business as usual'

Digitisation

Digital twins for turbine monitoring 'business as usual'

Significant reduction in people working offshore

Acceptance of robots and increased acceptance and adoption of autonomy

Adoption

Robots and people working collaboratively (symbiotic operations)

ROBOTICS ROADMAP 2040+

7

COST MODELLING

This section aims to quantify the impact of robotics in terms of OPEX and LCOE cost. In order to have greater confidence in the cost modelling results, two cost models have been used, one from Xodus and one from ORE Catapult. In the following sections, they will be referred to as "Model 1" and "Model 2", in no particular order, to maintain anonymity in the results. Moreover, the results will be presented as % differences of the original 2020 values and observations and not as actual OPEX and LCOE costs for confidentiality purposes.

Please note that the % differences shown in the following sections are only capturing the impact that robots will have with the information that is available today and has been collected in this work. This means that any advancements in the reliability of turbine components, vessel improvements and any other innovations that might drive the costs of operations down are not captured in this work.

7.1 Overview of cost models

The structure of the two cost models is shown below.

7.1.1 Xodus cost model structure

The Xodus OPEX model uses a bottom-up approach (as shown in Figure 7-1), starting from the individual failure rates and inspection intervals for the components. These are then aggregated and, depending on the maintenance strategy and the means of transport, the appropriate vehicle is used, and the weather is then factored in. The final offshore logistics costs are added to any fixed costs and the final OPEX value is calculated.

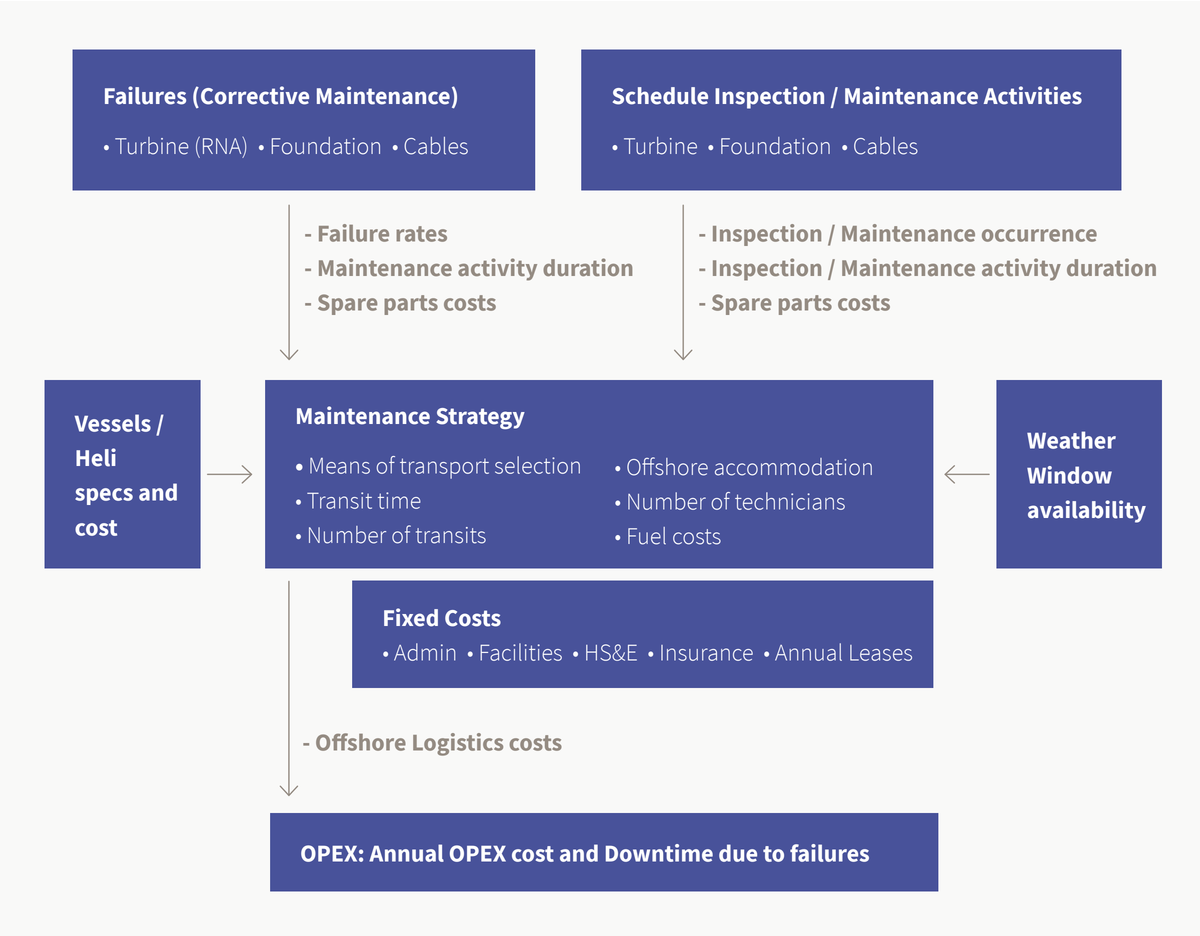

Figure 7-1: Xodus OPEX cost model high level structure

In the current version considered, the capital expenditure (CAPEX) and LCOE models that Xodus has developed are separate sheets. The CAPEX model follows a similar bottom-up approach and the values of the CAPEX and OPEX models are then inputted in the LCOE model, where any additional TNUoS charges, development expenditure (DEVEX), decommissioning expenditure (DECEX) are added and the annual energy production (AEP) is calculated from the power curve, which allows the calculation of the final LCOE estimate.

7.1.2 ORE Catapult cost model structure

ORE Catapult's offshore wind cost model is used to estimate the costs and potential returns from developing, constructing, and operating various offshore wind sites with specific physical and technology parameters. The model allows estimation of DEVEX, CAPEX, OPEX and DECEX, and makes a high-level estimation of AEP for different sets of site parameters; based on these, the model produces key financial indicators (including LCOE) based on all the financial inputs. An overview of the model structure is shown in Figure 7-2.

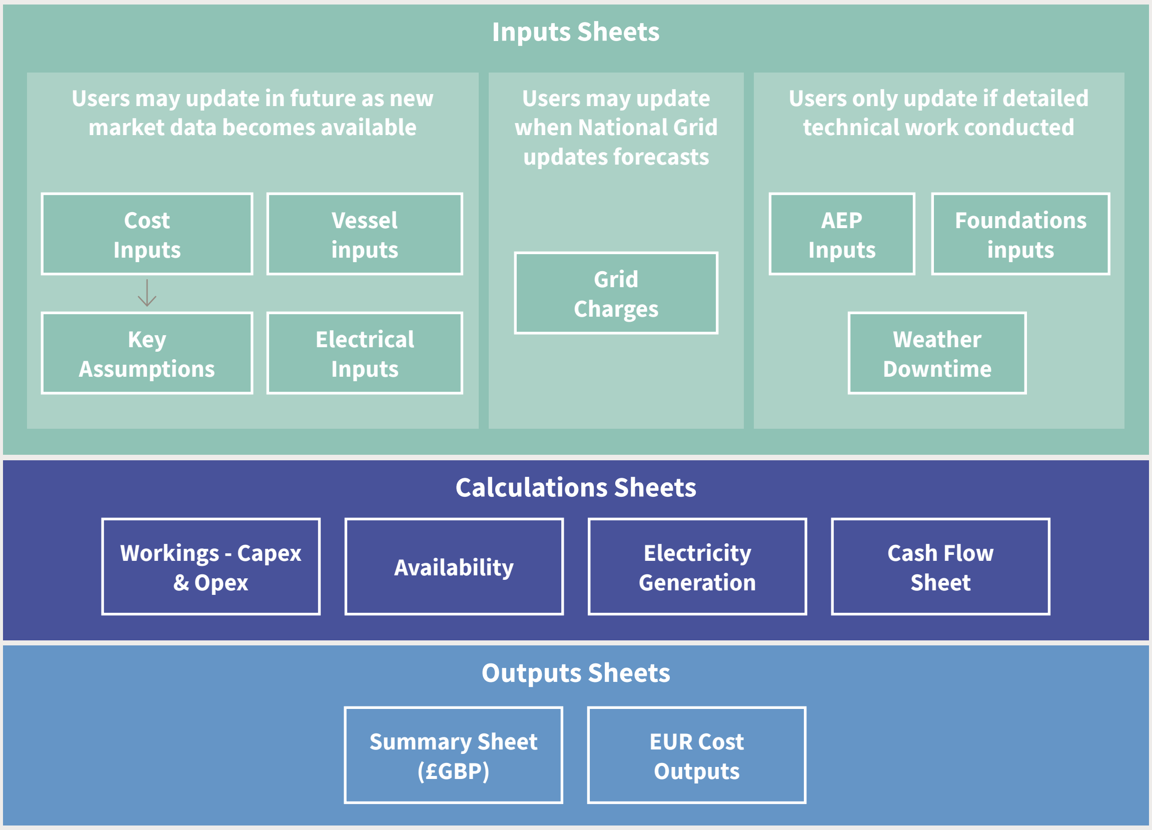

Figure 7-2: ORE Catapult offshore wind cost model structure (high-level)

The model inputs can be broadly categorised as:

- **Site-specific inputs**
  (e.g., locations, wind speed, turbine rating, foundation type, etc)
- **Technical and commercial assumptions**
  (e.g., price per wind turbine, number of days installation required per foundation, etc)

ORE Catapult led an analysis to compare offshore wind project costs in a range of markets as part of the International Energy Agency's Task 26 project [10]. Inputs were agreed across a number of leading research institutes to understand cost drivers for projects. The study was key in informing many of the technical assumptions underpinning the offshore wind cost model. A separate ORE Catapult cost model for floating wind farms has also been used for this report which follows the same principles.

7.2 Benchmarking

The Xodus OPEX model and the ORE Catapult offshore wind cost model were benchmarked using the reference case from a Guide to An Offshore Wind Farm [4]. The reference wind farm consisted of a hundred 10MW wind turbines (i.e., 1GW site capacity), located 60km offshore with a crew transfer vessel (CTV) based O&M strategy. Some of the OPEX inputs were fixed across both scenarios, such as project management and admin fees, operating facilities fees, health and safety costs, insurance, and annual seabed leasing charges. Transmission charges were omitted from the analysis. These fixed inputs stemmed primarily from the IEA Offshore Wind Farm Baseline documentation report [11], although expert judgement and other public data sources were used where appropriate. Fixing many of the OPEX inputs in this way meant that any differences between the two models were due to how the high-level data (i.e., farm size, turbines etc.) were interpreted. For the reference base case, as well as several variations to aspects such as distance from shore, the initial benchmarking exercises showed less than a 5% difference in OPEX values between the two models.

7.3 Cost model inputs and assumptions

7.3.1 Model fixed inputs

Both models, for the purposes of this study, utilized inputs from the IEA Offshore Wind Farm Baseline documentation report [11] in terms of spare parts costs, project management and admin fees, operating facilities fees, health and safety, insurance, and annual lease charges.

Category	(£/kW/year)	Source
Technicians	Calculated in the models	Multiple internal sources
Spare parts	5.74	[11]
Vessels	Calculated in the models	Multiple internal sources
Onshore electric maintenance	0.43	[11]
Operation, Management and Admin	2.43	[11]
Operating facilities	1.13	[11]
Environment and H&S	0.43	[11]
Insurance	18.26	[11]
Annual Lease and Fees	4.17	[11]
Failure rates	N/A	[12], [13]

Table 7-1: Cost modelling inputs

The rest of the inputs, with regards to vessels, technicians and maintenance interventions are determined by the individual models and include quotes, previous project experiences and other publicly available information. Weather downtime is also calculated in the individual models from previous project work.

A 30-year wind farm lifetime has been assumed and a 5% discount factor has been applied.

7.3.2 Timeline Scenarios

Four different timeline scenarios have been modelled, following the stakeholder engagement findings. An indicative timeline for the different scenarios is also shown. These are:

Increased number of robotic applications | 2025-2030

This scenario includes:

- Increased number of blade inspections with the use of UASs.
- Increased number of subsea inspections with increased use of AUV robots.

Semi-autonomy | 2030-2040

This scenario includes:

- BVLOS demonstrations and operations of a range of robotic applications.
- Full implementation of digital twin applications.
- Remote fault diagnosis with the use of resident robots and/ or advanced sensor systems attached to inspection robots.
- Higher level of robotic autonomy than vessel-based and supported inspections.
- Applications of collaborative robotics, with UAS, USV and AUV systems working in parallel operations and exchanging information with each other, where required.
- Initial demonstrations and application of resident systems for UAS, USV, AUV, internal and external crawler robot devices.

Full autonomy | 2040- 2050

This scenario includes:

- Application of full resident system solutions for UAS, AUV, USV and crawler devices, permanently based on the wind farm, with docking/ charging systems offshore and remote supervision from personnel based onshore.
- Independent robotic fleets, performing inspections when required and diagnosing alarms and potential faults.
- Initial manipulation tasks being demonstrated and perform light repair operations with the supervision of humans.

Plant of the future | 2050+

This scenario is looking at the “ideal” case and could be realised well after 2050, but shows the potential that robotic applications can offer with the knowledge that we have today and includes:

Infrastructure designed for robotics, expecting elements of the turbine, foundation, access systems, offshore substations to be designed mainly for easier access, inspection and fault finding from robotics, compared to what is traditionally designed today. This will require an effective implementation of inspection and maintenance strategies using robotics, with well proven turbine designs and the appropriate lessons learnt being fed back to the wind farm design stages.

All minor repair tasks performed by resident robots, eliminating the need for operational personnel having to travel offshore on a regular basis and increasing wind farm availability and H&S, as humans would need to travel offshore only for any major operations and component replacements.

7.4 Quantified inputs

A list of inputs to the models, as defined by the interviewees that participated in the stakeholder engagement exercise are shown in Table 7-2, which represent the base case inputs. A +/-20% variations of those cases have also been modelled to account for any uncertainties in the inputs. A few key assumptions for the inputs and their logic is shown below:

- The “As now” case represents 2020 figures and any percentage differences shown in the table are with 2020 as a reference year.
- The effect on labour is accounting for offshore personnel, as it accounts for marine operations. For most of the cases it is expected that the same number of people will be required to be placed onshore for remote monitoring or for analysing and reviewing the data received from the operations.
- In the occasions where time saved is considered “As now”, the speed that robotic devices (such as AUVs and UASs) are performing operations is taken into account, as well as the increased number of operations that will take place once more robotics are permanently placed offshore. These two will cancel each other out.
- The base cases defined for the 2020 scenario, are assuming the state of the art in robotic applications, including aerial drone deployments for blade inspections, AUVs for bathymetry inspections and ROVs for foundations inspections and any cost, time and labour savings are using them as base cases.
- Weather window availability is captured only in the table of inputs, vessel costs are not included as they are calculated in the models.

It should be noted that the views presented are from a range of stakeholders that might have had different views in terms of the commercial applications of certain technologies and in which timeframe these could be achieved and how big the percentage reduction would be; in those cases an approach presenting the average cases of the conflicting views was considered.

IMPACT OF ROBOTICS	Effect on Cost (%)				Effect on Labour (% or #, specified)				Time Saved (% or hours, specified)			
Parameter	**2025-2030**	**2030-2040**	**2040-2050**	**2050+**	**2025-2030**	**2030-2040**	**2040-2050**	**2050+**	**2025-2030**	**2030-2040**	**2040-2050**	**2050+**
Personnel Training	-5%	-10%	-15%	-20%	As now	As now	As now	As now	As now	As now	As now	As now
Inspections- H&S	20%	As now	-20%	-20%	As now	-50%	-60%	-80%	As now	As now	As now	As now
Inspections - Foundations, External	-15%	-20%	-30%	-40%	As now	-70%	-70%	-80%	-70%	-70%	-70%	-70%
Inspections - Foundations, Internal	As now	As now	As now	As now	-65%	-65%	-65%	-65%	-50%	-50%	-50%	-50%
Inspections - Array Cables	-15%	-20%	-30%	-40%	As now	-70%	-70%	-80%	As now	As now	As now	As now
Inspections - Export Cables	-15%	-20%	-30%	-40%	As now	-70%	-70%	-80%	As now	As now	As now	As now
Inspections - Cable Connection/J-Tube	-15%	-20%	-30%	-40%	As now	-70%	-70%	-80%	As now	As now	As now	As now
Inspections - Blades	-25%	-30%	-40%	-50%	As now	-70%	-70%	-70%	As now	-40%	-50%	-60%
Inspections - Moorings	As now	-50%	-50%	-50%	As now	-70%	-70%	-70%	As now	As now	As now	As now
Repairs - Foundations, External	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Repairs - Foundations, Internal	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Repairs - Array Cables	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Repairs - Export Cables	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Repairs - Cable Connection/J-Tube	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Repairs - Blades	-20%	-30%	-40%	-60%	-50%	-50%	-50%	-50%	-20%	-30%	-40%	-50%
Repairs - Moorings	-10%	-10%	-20%	-50%	As now	As now	As now	-50%	As now	As now	As now	As now
Insurance Costs	As now	-2%	-3%	-4%	N/A				N/A			
Weather Window availability	N/A				N/A				30%	50%	90%	90%

Table 7-2: Quantified inputs for the cost models, as generated from the stakeholder engagement (mid-range values). A +/-20% variability in the values is also taken into account when using those inputs for the different

The scenarios modelled are summarized in Table 7-3. The scenarios include a range of possible current and future wind farms, ranging from 500MW to 1GW fixed and floating sites with a range of turbine capacities, 10MW, 15MW and 18MW, at multiple distances offshore, with the different timeline scenarios explained in Section 7.3.2.

Scenario	Foundation	Farm Size	Turbine Capacity	Distance	Timeline	Weather	O&M Strategy
S1	Fixed	500MW	10MW	50km	2025-2030	Mild	CTV
S2	Fixed	500MW	10MW	50km	2030-2040	Mild	CTV
S3	Fixed	500MW	10MW	50km	2040-2050	Mild	CTV
S4	Fixed	500MW	10MW	50km	2050+	Mild	CTV
S5	Fixed	500MW	10MW	50km	2025-2030	Medium	CTV
S6	Fixed	500MW	10MW	50km	2030-2040	Medium	CTV
S7	Fixed	500MW	10MW	50km	2040-2050	Medium	CTV
S8	Fixed	500MW	10MW	50km	2050+	Medium	CTV
S9	Fixed	1GW	15MW	150km	2025-2030	Mild	SOV
S10	Fixed	1GW	15MW	150km	2030-2040	Mild	SOV
S11	Fixed	1GW	15MW	150km	2040-2050	Mild	SOV
S12	Fixed	1GW	15MW	150km	2050+	Mild	SOV
S13	Fixed	1GW	15MW	150km	2025-2030	Medium	SOV
S14	Fixed	1GW	15MW	150km	2030-2040	Medium	SOV
S15	Fixed	1GW	15MW	150km	2040-2050	Medium	SOV
S16	Fixed	1GW	15MW	150km	2050+	Medium	SOV
S17	Floating	1GW	18MW	150km	2030-2040	Medium	SOV
S18	Floating	1GW	18MW	150km	2040-2050	Medium	SOV
S19	Floating	1GW	18MW	150km	2050+	Medium	SOV
S20	Floating	1GW	18MW	150km	2030-2040	Harsh	SOV
S21	Floating	1GW	18MW	150km	2040-2050	Harsh	SOV
S22	Floating	1GW	18MW	150km	2050+	Harsh	SOV
S23	Floating	1GW	18MW	250km	2030-2040	Medium	SOV
S24	Floating	1GW	18MW	250km	2040-2050	Medium	SOV
S25	Floating	1GW	18MW	250km	2050+	Medium	SOV
S26	Floating	1GW	18MW	250km	2030-2040	Harsh	SOV
S27	Floating	1GW	18MW	250km	2040-2050	Harsh	SOV
S28	Floating	1GW	18MW	250km	2050+	Harsh	SOV

Table 7-3: Scenarios modelled

The fixed wind farm scenarios have been assumed to represent sites at shallower waters and closer to shore with distances at 50km and 150km, representing a range of potential project locations in UK and European waters, as well as other locations with longer continental shelf. They are modelled for all the identified timeline scenario, for mild and medium weather conditions, given their distance from the shore and O&M strategies using a CTV for the 50km cases and a SOV for the 150km cases. It is assumed that the sites will have 10MW and 15MW turbines, capturing the state-of-the-art technologies that will be installed in the next 5-10 years for 500MW and 1GW wind farm sizes.

The floating wind farm cases represent further offshore wind turbine locations at 150km and 250km with a 1GW total wind farm size. It is assumed that since those sites at scale will not be operational before 2030, only the 2030 onwards timelines are modelled. Moreover, since those sites are located further offshore, they are simulated for medium and harsh weather conditions.

7.5 Results

To preserve anonymity of the models and confidentiality of the key working inputs and outputs, the models have been named as “Model 1” and “Model 2” and the outputs are presented only as % changes and not as actual model outputs. This can be seen in Figure 7-4 through to Figure 7-7 . Table 7-4 shows the aggregated summary of the results from both cost models with a range of base case results and the maximum and minimum calculated OPEX, LCOE and availability percentage changes. This way the values can be extracted and used as multiplication factors at cost models more effectively. All outputs have been calculated for the base cases shown in Table 7-2 and the +/-20% uncertainty values.

The general differences between the models are due to the different calculations of the logistic scenarios in the models, the assignment of failure rates, the weather parameters, and calculations, as well as the sensitivity of the models in the input parameters.

Figure 7-3 and Figure 7-4 show the OPEX cost reduction outputs for fixed and floating sites. There is a difference in the models of up to 7.5% for the base cases and Model 1 shows consistently higher cost reduction potential for the first 4 fixed cases and for the 2050+ timeline scenarios of the fixed models, while Model 2 has higher cost reduction outputs for the majority of the floating wind scenarios at 250km offshore. For the 2025-2030 timeline (fixed cases only), there is a significant cost reduction from the increased use of robotics for inspection operations, expected for all the scenarios ranging from 5.5% to 7.8% for the base cases, with a potential of up to 9.5% and the lowest reduction being 3.7%. For the 2030-2040 timelines, where a level of semi-autonomy is expected to have been realised and initial resident systems to be present an OPEX reduction ranging from 7.7% to 14.6% is expected for the base cases of the fixed sites, with a potential of up to 16.5% and the lowest reduction being 6.5%. For the floating cases, the reduction base cases vary from 9.6% to 16.7% with a potential of up to 18.8% and the lowest reduction being 8%. The 2040-2050 timeline which includes the implementation of resident systems is expected to reduce OPEX for fixed wind farms from 10.9% to 16.5% with a potential up to 19.9% and the lowest reduction at 8.9%. For the floating cases, the base case range reduction is estimated from 11.4% to 19%, with the highest reduction expected at 21.2% and the lowest at 9.6%. Finally, the 2050+ timeline that includes savings that can be realised from infrastructure design improvements, the expected OPEX reduction for fixed wind farms is estimated from 12.5% to 21.8%, with a potential reduction of up to 27.1% and the lowest reduction at 10.8%. For the floating cases, the base case range reduction is estimated from 11.6% to 22.6%, with the highest reduction expected at 25.8% and the lowest at 11.4%.

Figure 7-5 and Figure 7-6 show the time-based availability output for both models. In terms of availability increase with the use of robotics for the fixed scenarios, time-based availability has a potential to increase with the range of scenarios from 0.23% to 1.87% in the base cases and up to 2.33% and the lowest increase expected at 0.19%. For floating, base case increases range from 0.31% to 1.44% with the maximum increase estimated at 1.71% and the minimum at 0.25%.

The equivalent LCOE reductions are shown in Figure 7-7 and Figure 7-8 and range from 1.9% to 8%, with a maximum reduction of 9.9% and a minimum of 1.3%, for the fixed scenarios and from 1.6% to 4.9% for the floating scenarios with a maximum reduction of 5.8% and a minimum of 1.4%.

In general, there is a trend in both models that shows that the further offshore the wind farms are located, the higher the contribution would be, as there are significant gains to be made in terms of transit time. Additionally, the more severe the weather conditions, the bigger the impact that robotics are expected to have, since there is still the element of transfer time, which is going to be eliminated when robotic resident systems will be present.

The contribution of OPEX in the fixed wind farm LCOE is higher than the one for the floating sites due to the lower installation and procurement costs compared to the floating sites. Thus, the overall LCOE change for floating wind farms is smaller compared to the fixed ones, even in cases where the OPEX % difference is higher than in the fixed scenarios.

	Fixed			**Floating**		
	Min (-20% from base case)	**Base case for both models** **(Table 7-2**: Quantified inputs for the cost models, as generated from the stakeholder engagement (mid-range values). A +/-20% variability in the values is also considered when using those inputs for the different**)**	**Max (+20% from base case)**	**Min (-20% from base case)**	**Base case for both models** **(Table 7-2**: Quantified inputs for the cost models, as generated from the stakeholder engagement (mid-range values). A +/-20% variability in the values is also considered when using those inputs for the different**)**	**Max (+20% from base case)**
2025 - 2030						
OPEX (-)	3.7%	5.5% - 7.8%	9.5%	-	-	-
Availability (+)	0.19%	0.23% - 0.91%	1.07%	-	-	-
LCOE (-)	1.0%	1.3% - 3%	3.5%	-	-	-
2030 - 2040						
OPEX (-)	6.5%	7.7% - 14.6%	16.5%	8.0%	9.6% - 16.7%	18.8%
Availability (+)	0.28%	0.34% - 1.33%	1.57%	0.40%	0.48% - 0.97%	1.18%
LCOE (-)	1.8%	2.1% - 4.6%	5.4%	1.4%	1.65% - 3.51%	3.9%
2040 – 2050						
OPEX (-)	8.9%	10.9% – 16.5%	19.9%	9.6%	11.4% - 19%	21.2%
Availability (+)	0.36%	0.44% - 1.44%	2.04%	0.52%	0.63% – 1.32%	1.52%
LCOE (-)	2.9%	2.4% - 5.7%	7.8%	1.6%	1.9% - 4.0%	4.7%
2050+						
OPEX (-)	10.8%	12.5% - 21.8%	27.1%	11.4%	11.6% - 22.6%	25.8%
Availability (+)	0.43%	0.53% - 1.87%	2.33%	0.61%	0.73% - 1.44%	1.71%
LCOE (-)	3%	2.7% - 8.0%	9.9%	1.95%	2.31% - 4.97%	5.9%

Table 7-4: Aggregated summary of cost models' results as % differences from 2020 cases

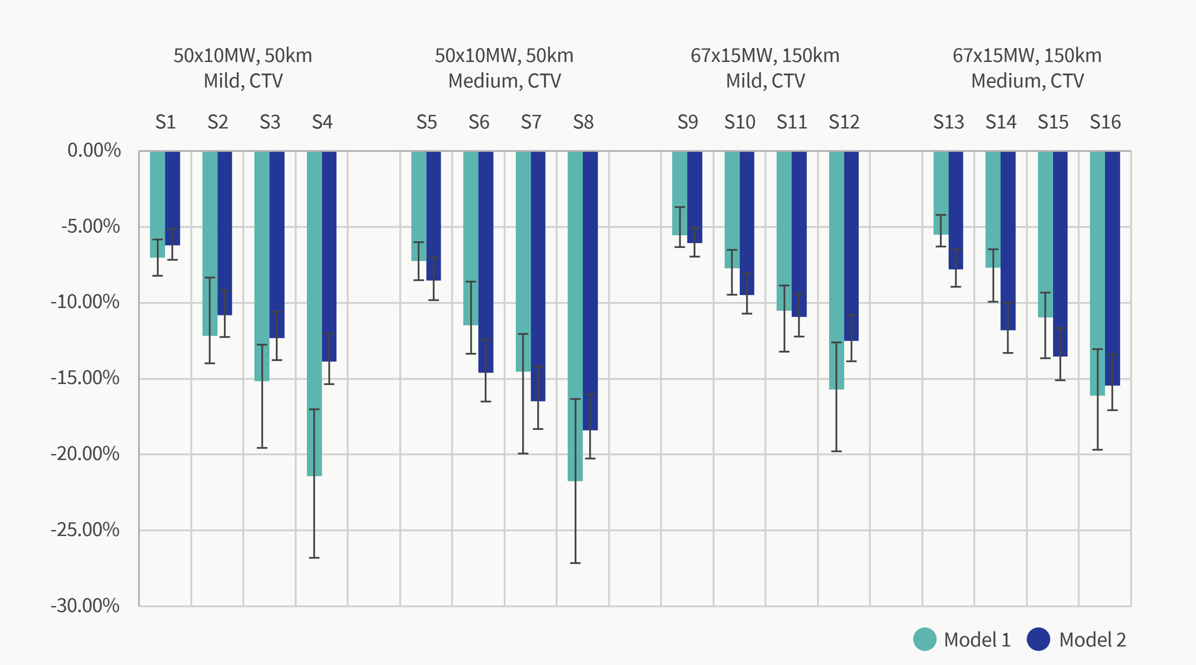

Figure 7-3: Models 1 & 2 OPEX % difference comparison from base case for all fixed scenarios, as defined in Table 7-3 .

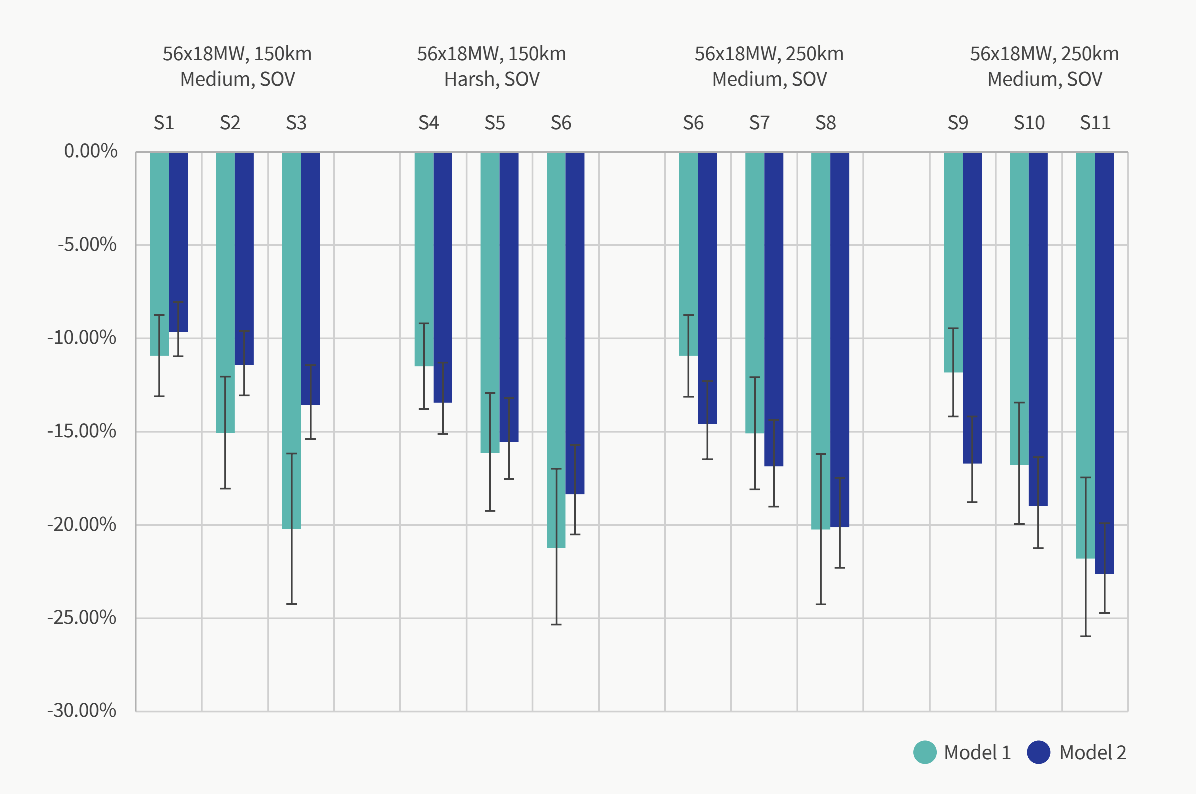

Figure 7-4: Models 1 & 2 OPEX % difference comparison from base case for all floating scenarios, as defined in Table 7-3

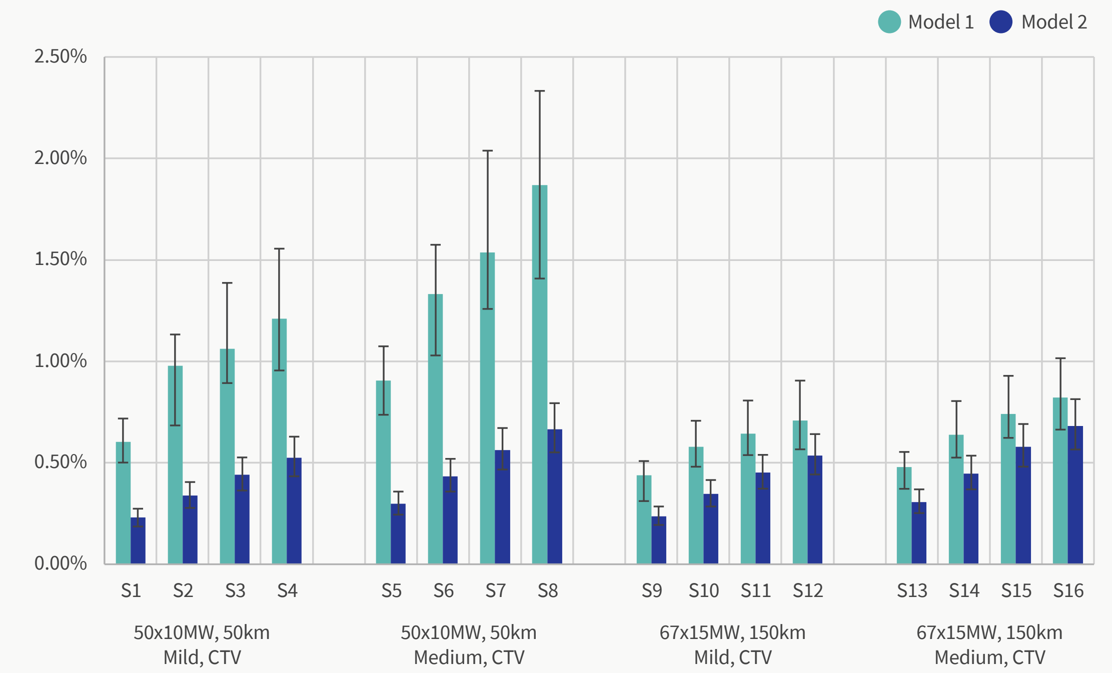

Figure 7-5: Models 1 & 2 time-based availability % difference comparison from base case for all fixed scenarios, as defined in Table 7-3

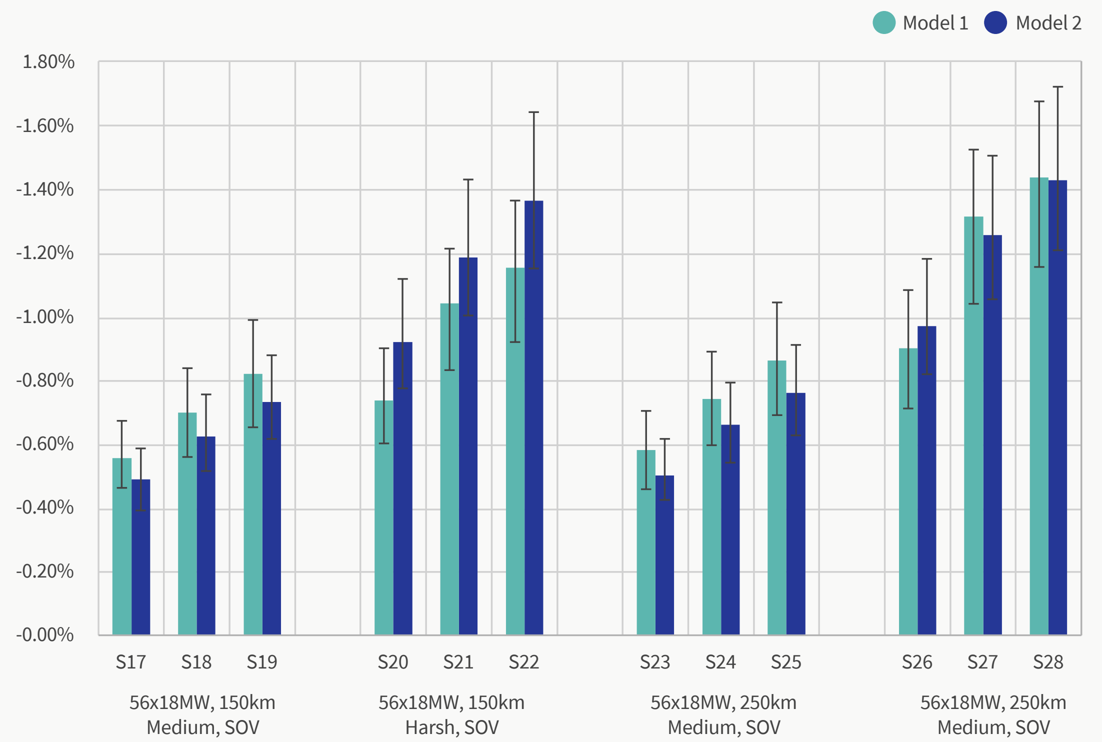

Figure 7-6: Models 1 & 2 time-based availability percentage difference comparison from base case for all floating scenarios, as defined in Table 7-3

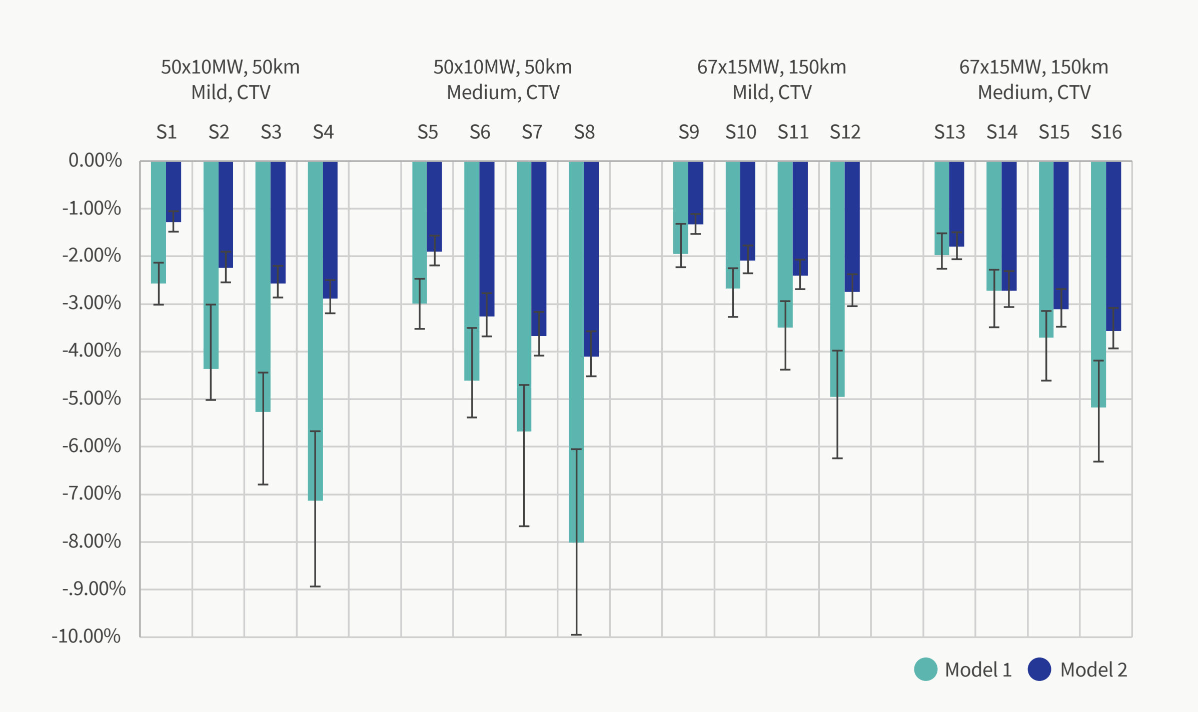

Figure 7-7: Models 1 & 2 LCOE % difference comparison from base case for all fixed scenarios, as defined in Table 7-3

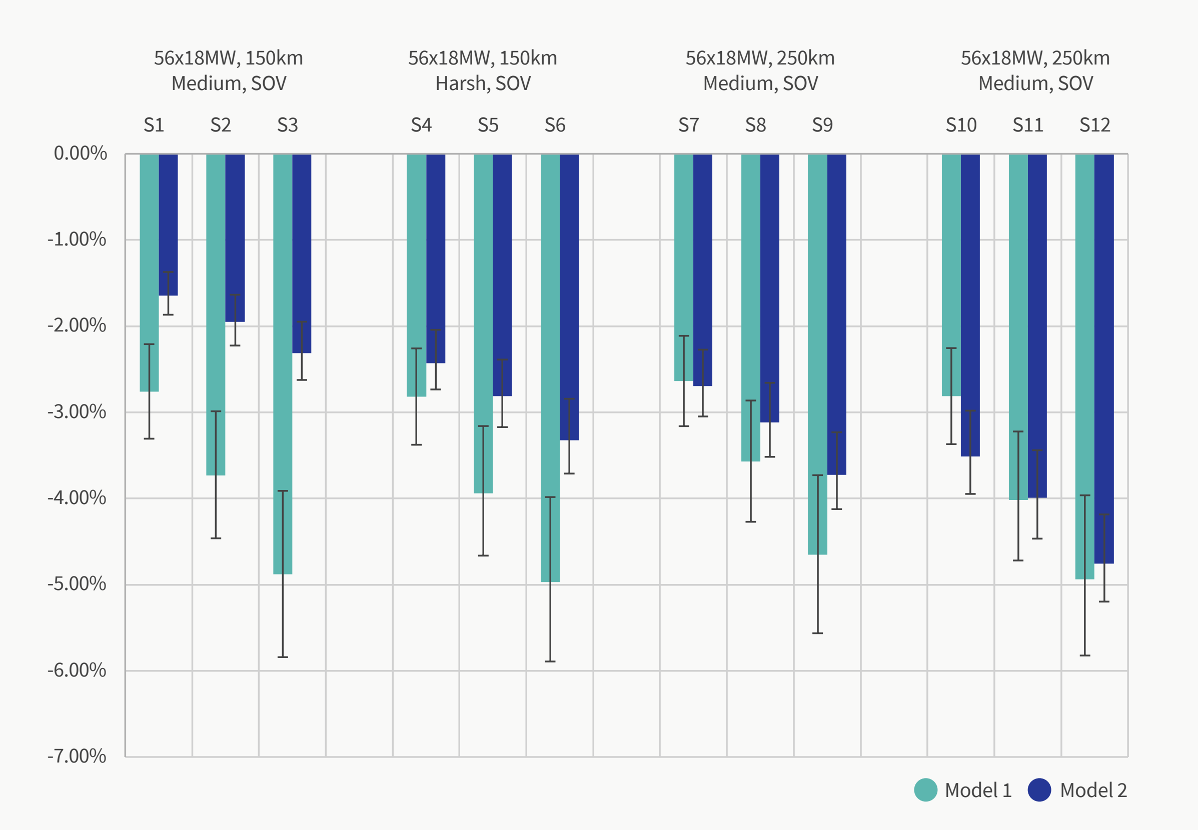

Figure 7-8: Models 1 & 2 LCOE % difference comparison from base case for all floating scenarios, as defined in Table 7-3

8

CONCLUSIONS

This report is one of the first attempts to analyse and understand the impact that robotics and autonomous systems will have in terms of cost reduction on the O&M phase of the offshore wind sector. The report has provided a detailed analysis of the robotics landscape in offshore wind for the next 30+ years, by engaging with a range of experts from industry and academia.

The outputs from this stakeholder engagement with AUV, UAS, ROV, USV, turbine crawler developers, service providers, cutting edge researchers, consultants and wind farm operators and wind turbine OEMs, has resulted in the definition of the state of the art in robotics for offshore wind applications in 2020, provided an understanding of the barriers and key risks that are preventing the adoption of robotics in offshore wind, highlighted the future value of robotics through a roadmap and finally quantified the impact of robotics in offshore wind O&M through their impact on OPEX and LCOE costs, as well as on the wind farm availability.

In the growing offshore wind energy industry, there is a continual drive toward cost reduction and improved safety in O&M activities. Both of these driving factors create an opportunity for implementing robotics and autonomous systems, however there has long been a need for improved mapping of this future landscape and quantifying the impact that robotic application would have in offshore wind.

The stakeholder engagement has identified the following strengths of robotics:

- ROVs are considered robust, reliable and can carry out most tasks' divers can;
- AUVs and autonomy is not common practice operationally, although it is being introduced and will continue to be over the next five years;
- The use of UASs for visual inspection is now common practice in the offshore wind sector and its adoption is seen as a role model for the wider potential robotics can bring to offshore wind; and
- The resident system approach for subsea, turbine crawler and aerial robots will significantly increase the weather windows operations can be carried out in because the platforms will be on-site ready to work whenever weather windows permit.

Some key areas that are deemed weak, in need of improvement, or preventing the full adoption of robotics include:

- Effectively communicating the economic benefits of robotics to end users;
- Significant further development of technology is still required to realise the future state-of-the-art mentioned in this report;
- Regulation and the relationship with regulators and other public authorities is seen as an area that could be improved to help the use and adoption of robotics;
- Common standards and standardisation is considered an area where there is an opportunity for improvement;
- A central supply chain interface is necessary to bring all the stakeholders together; and
- Social aspects related to the acceptance of robotics, such as human trust in the robots.

The UK has taken and continues to take significant strides in addressing the barriers highlighted in this report. Through the government's ISCF, the UK has invested significantly in bridging the gap between academia and industry so new technology developments and UK created IP finds its way into the global supply chain as quickly as possible. A large portion of funding has been directed towards creating collaborative academic-industry projects aimed at developing robotics and AI. An example of this is the ORCA Hub, funded through UKRI and managed by the EPSRC, and who co-authored this report. Moreover, the universities and companies are further supported in their offshore robotic developments by organisations such as the ORE Catapult – another co-author of this report, the Digital Catapult, and OGTC. The ORE Catapult and Digital Catapult provide both facilities and expertise to support companies and universities to transition and accelerate their ideas and developments into the market. OGTC provides another avenue of funding and connects technology developers with end users and potential customers. These organisations also support companies to better understand the economic benefit of their technical solutions, so they provide viable and competitive products and services. Additionally, in order to ensure the right personnel resources are available, EPSRC has funded several CDTs programmes that are educating and training individuals in areas of expertise related to offshore wind, robotics and autonomous systems.

Realising and overcoming the above barriers will enable the creation of the scenarios envisioned by the interviewees, which include; an increased number of robotic applications within the coming decade (2025-2030), applications of semi-autonomous systems in 2030-2040, full autonomy and resident systems from 2040 onwards, leading to the plant of the future later on that will include a feedback loop into the offshore infrastructure design process for greater improvements.

Using the above findings, 28 scenarios were modelled using Xodus' and ORE Catapult's cost models. The results highlighted that:

- Robots can add greater value at wind farms that are placed further offshore with more extreme weather conditions, compared to closer to shore sites. This is due to the fact that resident systems can significantly reduce transit time and can reduce the waiting on weather.
- Robotics will have a larger overall impact in the OPEX of floating wind compared to fixed wind, but both cases show very promising results
- Aerial robotics for internal and external inspections seem to have a higher cost reduction potential compared to subsea ones in the short them, however, innovations in the subsea space will be accelerated in the coming years and those cost reductions will be realised in the medium to longer term.
- Largest cost savings will be realised from the increased number of autonomous inspection and the more data-driven decision making that this offers, compared to any savings from remote repairs and component replacements that will probably won't be realised as much within the timeframe examined in this report.
- There is a potential cost savings for all the different scenarios and timelines for a fixed wind farm, ranging from up to 9.5% in OPEX reduction (3.5% in terms of LCOE) by the end of the decade to up to 27.1% (9.9% in terms of LCOE) once all robotic innovations have been realised and an availability increase of up to 1.07% and up to 1.87% respectively.
- For the floating scenarios, the results are ranging from up to 18.8% in OPEX reduction (3.9% in terms of LCOE) by the end of 2040 and up to 25.8% (5.9% in terms of LCOE) once all robotic innovations have been realised and an availability increase of up to 1.18% and up to 1.71% respectively.

Future work that can be based on the results and approach of this report includes:

- A detailed analysis specifying when the barriers will need to be removed for the robotics projections to be realised on time and as per the roadmap predictions. Moreover, this study should also capture the view of the certification bodies in order to create a more accurate representation of the timeline.
- A detailed analysis of the size of the robotics market in offshore wind O&M and the potential revenue streams for robotics developers and service providers.
- Quantifying the impact of robotics during the pre-construction, manufacturing and installation stages of an offshore wind farm.
- Following the format of this work, smaller case studies can be generated for individual technologies (such as UASs), or product specific case studies for individual technology developers that can help them realise the potential of their service and create a more robust business case for it.
- Investigation of the influence that sensors and IoT can have in the acceleration of the deployment of robots and identify any potential showstoppers that would need to be addressed.

REFERENCES

1 Offshore Renewable Energy Catapult, Knowledge Transfer Network, “Operations & Maintenance: Cost Drivers,” Offshore WInd Innovation Hub, 2019.

2 M. Noonan, “Delivering 40GW – Accelerating the UK’s Transition to Net Zero,” ORE Catapult, 30 September 2020. [Online]. Available: https://ore.catapult.org.uk/blog/delivering-40gw-accelerating-the-uks-transition-to-net-zero/. [Accessed 17 December 2020].

3 BVG Associates, “Expertise. LCOE,” 2020. [Online]. Available: https://bvgassociates.com/our-expertise-economic/. [Accessed 17 December 2020].

4 ORE Catapult, “A Guide to an Offshore Wind Farm,” 2020. [Online]. Available: https://guidetoanoffshorewindfarm.com/wind-farm-costs. [Accessed 17 December 2020].

5 G+ Global Offshore Wind Health & Safety Organisation, “G+ Global Offshore Wind Health & Safety Organisation 2019 incident data report,” 2019.

6 G+ Global Offshore Wind Health & Safety Organisation, “G+ Global Offshore Wind Health & Safety Organisation 2019 incident data report summary for technicians,” 2019.

7 International Renewable Energy Agency (IRENA), “Future of Wind. Deployment, investment, technology, grid integration and socio-economic aspects,” 2019.

8 M. Koziol, “Amazon’s Project Kuiper is More Than the Company’s Response to SpaceX,” IEEE Spectrum, [Online]. Available: https://spectrum.ieee.org/tech-talk/aerospace/satellites/amazons-project-kuiper-is-more-than-the-companys-response-to-spacex. [Accessed 17 December 2020].

9 CB Insights, “From Energy To Transport To Healthcare, Here Are 8 Industries Being Disrupted By Elon Musk And His Companies,” 2020. [Online]. Available: https://www.cbinsights.com/research/report/elon-musk-companies-disruption/#telco. [Accessed 2020 December 17].

10 EDF Renewables, “Linkedin,” July 2020. [Online]. Available: https://www.linkedin.com/posts/edf-renewables_offshore-windpower-renewableenergy-activity-6691598133765394432--bQ2/. [Accessed 17 December 2020].

11 IEA Wind TCP Task 26, “Offshore Wind Energy International Comparative Analysis,” National Renewable Energy Laboratory, 2018.

12 National Renewable Energy Laboratory, “IEA Task 26- Offshore Wind Farm Baseline Documentation,” 2016.

13 J. Carroll, A. McDonald and D. McMillan, “Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines,” Wind Energy, vol. 19, no. 6, pp. 1107-1119, 2015.

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