

FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

PR43: APPLICATION OF REMOTE AND AUTONOMOUS SYSTEMS (RAS) FOR FOW CONSTRUCTION, INSTALLATION, OPERATIONS AND MAINTENANCE ACTIVITIES



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PREFACE

Floating offshore wind (FOW) projects will face additional inspection and maintenance challenges compared to conventional bottom fixed wind projects due to the nature of FOW technology, the increased project distance from shore, and the harsher weather conditions this implies. To address some of these challenges, remote and autonomous systems (RAS) could be applied. The capability of these technologies is continually improving, and some have already been applied in the adjacent industries of bottom fixed wind and oil and gas. The aim of this project was therefore to determine the potential for RAS application in FOW construction, operations and maintenance.

To achieve this aim, three research questions were formed:

1. Which floating wind project activities could present suitable use cases for RAS application?
2. What remote and autonomous technologies currently exist which could be used on FOW projects, and what are some key considerations in their application?
3. What are the potential impacts and benefits of using RAS compared to conventional methodologies?

To address these questions, this report presents the findings of research performed via literature review, assessment of ORE Catapult internal knowledge, stakeholder engagement questionnaires and interviews, and internal cost modelling.

First, a representative overview of different remote and autonomous technologies is provided. This includes some of the key characteristics of uncrewed surface vessels (USVs), subsea remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and unmanned aerial vehicles (UAVs). A review of floating wind farm offshore activities is then combined with stakeholder engagement findings to identify the most suitable use cases for RAS as part of a FOW project. Tasks which are highly repetitive across identical assets, for example inspection of subsea components such as mooring systems, substructures and cables, are highlighted as highly suitable use cases for autonomous systems. Other activities, such as seabed surveys, are also highlighted as suitable use cases for remotely operated or autonomous technologies.

Some key considerations for RAS application for FOW are then discussed, including autonomy and human intervention levels, communications/data transfer requirements, operational requirements, and regulation. Operational considerations, including task duration and scope, operational weather limits, and launch and recovery requirements are discussed. Dynamic motion of floating structures is highlighted as a challenge for inspection activities, though the impact will vary based on motion; guidance on expected amplitude and frequency of component motion can help the supply chain address potential issues. Recent UK regulatory guidance relevant to application of remote and autonomous technologies is then summarised, finding that regulatory bodies are in the process of developing their requirements in this area.

Potential benefits that could be achieved through the appropriate application of RAS in FOW projects were found to include reduced cost, increased operational efficiency, improved health and safety through reduction or removal of personnel offshore, and reduced vessel emissions through the use of smaller, more efficient technologies. Various challenges facing the adoption of RAS in offshore wind identified through stakeholder engagement and other project activities are summarised. Key points raised included that there is currently limited understanding of clearly defined scopes of work for floating wind construction and maintenance activities from a supply chain perspective. Potential enablers to support wider RAS adoption are then identified, including continued collaboration and

engagement across the industry to support market clarity and direction, increased opportunities for technology testing and demonstration, and workforce upskilling and training.

Finally, the estimated duration and cost of two floating wind RAS-based subsea inspection campaign case study scenarios are modelled and compared to a baseline approach of inspection campaigns using a conventional tethered ROV with support vessel. Scenario 1, representing the use of a remotely operated USV with ROV, found slightly increased campaign durations and slightly lower cost compared to the conventional approach; there was a significant reduction in personnel time offshore to carry out the inspection campaign. Scenario 2, representing the addition of two AUVs to support the baseline inspection campaign approach, led to a significantly reduced campaign duration which subsequently reduced the campaign cost. These case studies highlight the potential scope for uncrewed technologies to reduce personnel time in harsh offshore environments and examine the potential time and cost savings from implementing uncrewed operations.

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NOMENCLATURE

AHV	Anchor Handling Vessel
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AUV	Autonomous Underwater Vehicle
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BVLOS	Beyond Visual Line of Sight
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CAA	Civil Aviation Authority
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CLV	Cable Laying Vessel
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CoE	Centre of Excellence
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CRI	Commercial Readiness Index
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CTV	Crew Transfer Vessel
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DARE	Digital, Autonomous and Robotics Engineering
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EU	European Union
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FOW	Floating Offshore Wind
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FOW CoE	Floating Offshore Wind Centre of Excellence
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FOWT	Floating Offshore Wind Turbine
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Hs	Significant Wave Height
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ICAO	International Civil Aviation Organisation
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IMO	International Maritime Organization
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MASS	Maritime Autonomous Ship Systems
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MCA	Marine and Coastguard Agency
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MRU	Motion Reference Unit
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NDT	Non-Destructive Testing
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ORE	Offshore Renewable Energy
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O&G	Oil and Gas
O&M	Operations and Maintenance
RAS	Remote and Autonomous Systems
ROC	Remote Operations Centre
ROUV	Remotely Operated Unmanned Vessel
ROV	Remotely Operated Vehicle
ROVSV	ROV Support Vessel
SOV	Service Operation Vessel
UAV	Unmanned Aerial Vehicle
UN	United Nations
USV	Uncrewed (or Unmanned) Surface Vessel
VLOS	Visual Line of Sight

1 INTRODUCTION

Floating offshore wind (FOW) will be a key technology in the delivery of net zero targets. FOW projects currently under development will be located in deep water locations, generally further from shore and in harsher weather conditions than conventional bottom fixed wind. The combination of site conditions and long transit distances will lead to reduced accessibility and weather windows for carrying out inspection and maintenance tasks using traditional methods. In contrast to the oil and gas industry, FOW is not expected to use divers for O&M of subsea assets.

Simultaneously, the capability of remote and autonomous systems (RAS) with the potential to support offshore wind activities is rapidly improving. The use of these technologies could fundamentally change how some activities are carried out offshore, with subsequent benefits for health and safety, cost, and vessel emissions. However, there are still a range of uncertainties associated with the widespread adoption of remotely operated and autonomous systems in floating offshore wind.

The aim of this Floating Offshore Wind Centre of Excellence (FOW CoE) Project, *PR43: Application of Remote and Autonomous Systems (RAS) for FOW Construction, Installation, Operations and Maintenance Activities*, is to investigate the applicability of RAS in FOW projects, by addressing the following questions:

- What activities during a floating offshore wind project can be carried out by RAS and how could this benefit the FOW industry?
- What remote and autonomous technologies currently exist to carry out these activities, and what innovations and developments could be put in place to improve their performance and applicability to FOW?
- What are the potential impacts and benefits of using RAS compared to conventional methodologies for offshore wind project activities?

These questions are addressed throughout this report within the following sections:

Section 2: Project Approach and Stakeholder Engagement – provides brief outline to approaches and the Stakeholder Engagement Process.

Section 3: Overview of Remote and/or Autonomous Technologies – presents a summary of different robotic systems which can potentially be used to support FOW farm activities, including Uncrewed Surface Vessel, Remotely Operated Vehicle, Autonomous Underwater Vehicle (AUV), and Unmanned Aerial Vehicle (UAV) technologies.

Section 4: Floating Offshore Wind Activity Review – identifies areas of highest RAS applicability and potential benefit for floating wind farms.

Section 5: Key Considerations for RAS Application –describes some key considerations for RAS application that were identified over the course of this project, including a) the level of autonomy, b) offshore communications and data transfer, c) operational requirements, and d) regulatory requirements.

Section 6: Potential Benefits of RAS Application in Floating Wind – provides a summary of the potential benefits which can be realised through the use of RAS for a floating offshore wind project (cost, health and safety, emissions reduction).

Section 7: Current Challenges for RAS Application in Offshore Wind and Potential Enablers – outlines some of the current challenges to the RAS application and highlights some of the potential enablers.

Section 8: Case Study FOW Subsea Inspection –presents an O&M modelling analysis of FOW farm planned subsea inspection campaigns using ROVs from an onshore remote operations centre and using multiple AUVs deployed from an offshore support vessel. Provides a quantitative example of the impact on campaign duration and cost, and personnel hours offshore.

Sections 9 and 10 – Section 9 then summarises the main conclusions and Section 10 highlights some recommendations and potential steps to support the continued development of RAS.

2 PROJECT APPROACH AND STAKEHOLDER ENGAGEMENT

Overview of Approach

The information, findings, and conclusions presented in this report are based primarily upon the following information sources:

- Publicly available literature (e.g. industry reports, research journals, regulatory guidance);
- ORE Catapult internal knowledge, both from previous studies and practical experience running testing facilities;
- Engagement with key stakeholders: floating offshore wind developers (the CoE Constructions and O&M Focus Group) and supply chain stakeholders;
- O&M modelling analysis completed using ORE Catapult’s internal O&M cost modelling tool, COMPASS.

2.1.1 Stakeholder Engagement Process

Stakeholder engagement for this project was carried out both through the use of questionnaires and through interviews and discussions with stakeholders. 12 questionnaire responses were received, including responses from Forsea Robotics, Fugro, Nauticus, Oceaneering, Perceptual Robotics, Principle Power, Rovco and Vaarst, and Sonardyne. Follow-up interviews were held with a majority of those contacted. ORE Catapult would like to thank everyone who provided input into the Stakeholder Engagement process.

3 OVERVIEW OF REMOTE AND/OR AUTONOMOUS TECHNOLOGIES

Remotely or autonomously operated technologies have the potential to support project activities on floating offshore wind farms. This includes uncrewed surface vessels (USVs), subsea vehicles such as remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), unmanned aerial vehicles (UAVs), climbing or crawling vehicles, or a combination of these to extend support capability. This section summarises a selection of currently available technologies, highlighting key specifications, capability, and targeted use cases

Uncrewed Surface Vessels (USV)

USVs operate at the water level and are smaller than typical crewed vessels used in offshore wind. They can generally accommodate different equipment payloads, held within the vessel's 'gondola' below the water surface. Launched from shore or a vessel offshore (with a suitable lifting apparatus), these vessels can be operated from an onshore control centre and carry out offshore tasks autonomously or semi-autonomously. They can also act as support for linking subsea vehicles as a surface communications.

Vessel endurance (the amount of time they can spend offshore) is variable depending on its operational profile. However, some of these technologies state endurance values of up to multiple weeks.

Subsea Vehicles

Subsea technology is routinely used by the offshore oil and gas and renewable energy industries for inspection, monitoring, and maintenance of assets in areas that are otherwise inaccessible to marine personnel. The industry is developing new technologies for underwater applications to minimize the O&M costs and personnel requirements while also improving aspects of safety and reliability.

Subsea vehicles, such as ROVs, will be required as part of floating wind farm installation to carry out monitoring of subsea operations such as mooring and cable installation. They can also be used to support the recovery of pre-laid assets such as mooring lines as part of floating wind turbine hook-up. Subsea vehicles can also be used in the O&M phase of a floating wind farm to carry out activities such as surveys of mooring lines, cables, substructures, etc.

3.1.1 Remotely operated vehicles (ROVs)

ROVs are versatile subsea vehicles with the ability to navigate complex underwater environments and reach areas that are difficult to access. They can manoeuvre around subsea structures and inspect critical components using high-resolution cameras, sensors, and manipulator arms. ROVs are generally operated through a tether from a crewed support vessel offshore. However, untethered ROVs operated from either vessels or onshore Remote Operating Centres (ROCs) are beginning to see uses in offshore wind and other industries such as oil and gas.

ROVs are classified based upon their operational capabilities. Classes I and II constitute observation-class vehicles with the ability to mount various sensors such as SONAR, high-definition camera, and lights. Class III includes work-class vehicles with the ability to mount small manipulators in addition to more advanced sensors. Class IV vehicles are pulled through the water by a surface craft. These are heavier vehicles and are normally designed to carry out a specific underwater task such as burial of cables. Class V includes AUVs that are untethered, have higher autonomy and manoeuvrability, and can carry out inspection and mapping tasks. It is noted that some classifications can be broad and potentially outdated as technology develops. AUVs are often considered separately.

3.1.2 Autonomous underwater vehicles (AUVs)

AUVs can be used to inspect floating offshore wind farm components or carry out subsea survey activities. AUVs operate autonomously without the need of a tether or a remote-control system.

However, currently these systems generally have some level of human supervision. AUVs can follow pre-programmed routes to collect sensor data around foundations, anchors, and cables. Most conventional AUVs are linearly propelled and therefore cannot effectively navigate around structures to carry out close inspection tasks. However, AUVs with hovering capability and the capability to navigate in six degrees of freedom around structures are being developed.

The lack of tether removes tether management considerations. However, AUVs generally have lower endurance capability and will have to dock and recharge for long duration activities. The removal of the tether also limits the amount of data that can be transferred in real time when vehicle is operating subsea, therefore payload data is often recovered upon resurfacing rather than being transferred in real time. Some AUVs or hybrid AUV/ROVs operate with fibre-optic tethers to support real-time data transfer.

Unmanned Aerial Vehicles (UAVs)

The use of UAVs, often referred to as aerial drones, for the inspection of industrial assets is well established. They can access difficult-to-reach areas and capture high-resolution imagery, offering a range of potential benefits for the challenging inspections required on an offshore wind turbine, including blade inspections and above-water sections of the substructure and secondary steel. This offers a potentially safer, more efficient, and cost-effective alternative to conventional approaches such as rope access technicians. There are also examples of UAVs being used in other industries to carry out internal tank inspections, which could be relevant to floating wind substructure internal inspections.

Equipped with advanced sensors, cameras, and even thermal imaging technology, aerial drones can detect and document potential structural issues, such as leading-edge erosion, lightning detector damage, surface corrosion or wear and tear, without the need for human technicians to physically climb turbines. This can reduce the risk of accidents along with minimising downtime and operational disruptions. The data collected by UAVs during inspections can be analysed and processed using artificial intelligence algorithms to identify anomalies and patterns, allowing for proactive maintenance and timely repairs. Autonomous UAV technology is also currently being developed with offshore wind use cases in mind.

Climbing / Crawling Vehicles

Climbing robots, or crawlers, are robotic systems with the ability to attach onto and move along the surface of the turbine tower or the blade, including rotating over the blade edge. This enables access to areas difficult for human technicians to reach, such as blade tips, allowing for more thorough inspections. Equipped with advanced sensors, cameras, and even non-destructive testing equipment, climbing robots can detect issues such as cracks, delamination, erosion, or lightning strike damage. This eliminates the need for human climbers, enhancing safety and reducing the risk of accidents.

Crawlers are also used in other offshore industries to carry out inspection, non-destructive testing (NDT) activities, and cleaning of structures subsea. Subsea crawlers maintain contact with the structure by using permanent or electro-magnets, or by creating a pressure difference between the crawler and the surface, allowing access to areas challenging for divers or ROVs.

Vehicle Combinations

Combining technologies can extend their capability; three examples are discussed below.

3.1.3 USV with ROV / or AUV

USVs can function as a launch platform for ROVs. Equipped with launch and recovery systems, this heterogeneous system takes advantage of the USV endurance and range with the subsea manoeuvrability and sensor payload of ROVs. This approach could support wind farm operators in completing remotely operated subsea inspection of foundations, cables, and subsea infrastructure and light intervention while eliminating the need for offshore personnel.

3.1.4 USV with UAV

USVs can also serve as launch platforms for unmanned aerial vehicles, allowing drones to operate further offshore to inspect wind turbine blades, towers, and nacelles above the surface. The heterogeneous USV-UAV combination provides both aerial and sea surface perspectives to identify damage or defects on turbines or above water sections of the substructure, potentially removing the requirement for rope-access technicians.

3.1.5 Resident systems

Another option is resident robotic systems permanently situated at the offshore wind farm. These ROVs remain offshore and can carry out inspection and maintenance tasks on demand. This potentially allows for faster activities without long transit times, support vessels, or human intervention, but would have to outweigh the cost of having permanently situated systems.

Remote Sensors and Digital Twins

Other approaches to remotely understand the condition of offshore assets in a floating wind farm include the use of various sensors and digital twin systems.

3.1.6 Sensors

Sensors are used as remote monitoring systems to detect mooring system failure and better understand performance by tracking aspects such as mooring line tension, line inclination, substructure position, and motion. Mooring line tension can be directly measured using load cells, and can detect failure through a large decrease in line tension. This can also be used to inform fatigue assessment, though issues have been highlighted around accuracy, reliability, and robustness of such systems [1]. Substructure monitoring systems can track position, motion in six degrees of freedom, and monitor structural integrity of the substructure hull. The position of the structure and motion in response to environmental conditions can be used to determine mooring system failure.

Other methods of location tracking include GPS, used at the Kincardine Floating Offshore Wind Farm [2], and Motion Reference Units (MRUs), which can monitor motion and responses. Motion response of the substructure, accompanied by strain gauge measurements, can allow for understanding environmental loading on substructure and measure strain at high risk areas. However, strain gauges have been found to have challenges such as corrosion in offshore environments [3].

Monitoring techniques such as distributed temperature sensing and distributed acoustic sensing can be used to detect potential issues in electrical cables. There are examples of these systems being used in offshore wind export cables [4], [5].

3.1.7 Digital Twins

Digital twin systems lead to a more risk-based inspection and maintenance approach where interventions are initiated on the basis of evidence, rather than as a time-based schedule. The use of digital twins to understand performance of components including the mooring system, dynamic cables, and floating substructure has been highlighted as an area of interest; digital twins allow for a better understanding of asset performance during operation to inform decision making during the design phase. Digital twin systems consist of three main parts: the real system, the virtual system, and information sharing between the two. System creation should follow three steps [6]:

1. Data acquisition
2. Model creation and/or model update/validation
3. Real asset and model integration

When combined with appropriate analytical tools and models, the asset performance can be understood in real time [7]. The use of digital twin has been used to monitor mooring line fatigue, where accelerometers, gyroscopes, and satellite positioning were used to monitor the behaviour of a FOW turbine. Converting the collected data into mooring line tension cycles was then achieved using a transfer function made by modelling turbine response to wind and wave conditions [8].

4 FLOATING OFFSHORE WIND ACTIVITY REVIEW

Introduction

The aim of this section is to identify the activities over the lifetime of a floating wind farm project which a) present a highly applicable use case for RAS technology, and b) are unique to floating offshore wind. This was done through an initial screening analysis completed by ORE Catapult combined with findings from the stakeholder engagement process (described in Section 2). Supply chain stakeholders were asked to provide input on a) the FOW use cases which they were targeting, and b) in general, where they thought the main opportunities and use cases were for RAS to support FOW.

The lifecycle of a floating wind farm project was separated into three main offshore phases: pre-construction surveys, wind farm Installation, and operations and maintenance. Activities relating to each of these phases were identified based on ORE Catapult's knowledge from previous projects. Each activity was then given a 'Red', 'Amber', or 'Green' (RAG) rating based on whether it was considered to be an activity specific to floating offshore wind, and another RAG rating based on whether it was considered to have a clearly applicable RAS use case, based on the review of RAS technology previously presented in Section 3 and ORE Catapult's internal knowledge. 'Green' activities are those which are considered to have clear use cases for remotely operated or autonomous technologies beyond the current approach. 'Amber' activities are those which are considered to be possible, but may only be applicable to a small part of the activity or may not present clear benefit. 'Red' activities are those that are thought likely not applicable for RAS use currently or in the near future. An example of the results from this screening process can be found in Table 1.

Table 1. Example from screening of FOW activities for RAS application.

Installation				
Export Cable Installation			FOW Specific?	RAS Applicable?
Route Pre-Lay Grapnel Run	Export Cable	Used to clear debris along the cable route prior to cable laying activities. Generally using a vessel with a towed grapnel chain along the seabed. Not FOW-specific. Requires towing of heavy grapnel, so not currently applicable for RAS.		
Shore Cable Pull in	Export Cable	Cable is pulled into shore and connected to static onshore HV cable. Not FOW-specific. Not considered applicable for RAS.		
Cable Laying and Burial	Export Cable	Cable is laid by CLV and can either be simultaneously buried using a cable plough, or subsequently buried using a trenching ROV which moves along the seabed. ROVs are used to observe the cable laying process and can be used to carry out post-installation surveys. Not FOW-specific. It is expected that cable laying vessels will have onboard ROV capability and live, human feedback is required during operation, therefore there may not be benefits in RAS solutions beyond conventional ROV. ROVs operated from shore, AUVs, or USVs could be used to carry out post-installation surveys.		
Pull-In at Substation	Export Cable	Cable is pulled into the offshore substation. This will include the cable end being connected to a messenger wire at the I-Tube/J-Tube and then being pulled in through the J-Tube using a winch. During this process, an ROV is used to connect the cable pull-in head and the messenger wire and may also be used to observe throughout the operation. Not FOW-specific. It is expected that cable laying vessels will have onboard ROV capability and live, human feedback and operation is required during operation, therefore there may not be benefits beyond conventional ROV.		

Pre-Construction Surveys

There is significant scope for RAS to support pre-construction activities which require surveying of the sea bed. There is significant overlap between current geophysical survey methods (done using large, crewed survey vessels) and the use-cases targeted by USVs and AUVs. Technologies such as multi-beam echosounder, side-scan sonar, and sub-bottom profilers are generally used to map the seabed conditions for an offshore wind farm site. USVs are already being used, or are planned to be used, in offshore wind projects to complete geophysical surveys, and are undergoing development by some offshore wind developers [9]. Seabed mapping is also a suitable use case for autonomous underwater vehicles.

Wind Farm Installation

Floating wind farm installation activities will be carried out using large vessels, such as anchor handling vessels (AHV), cable laying vessels (CLV), and tug vessels with no clear scope for RAS to replace these. Currently, ROVs are expected to support installation through observation of subsea operations, carrying out connection and disconnection at the interfaces between subsea components, substructure, and vessel, and providing as-built surveys after the operation has been completed. It is possible that ROVs operated from an ROC could be used to carry out these tasks or AUVs used to carry out survey activities. However, as AHVs and CLVs are generally equipped with existing on-board ROV capability and subsea operations during installation can be intricate and highly variable, there is limited scope for additional RAS application beyond the current standard.

Operations and Maintenance

- Stakeholder engagement emphasised inspection and minor maintenance activities, such as cleaning and NDT, of subsea assets as the highest priority area for RAS application. O&M activities considered most applicable are those which are: carried out regularly across the wind farm
- are carried out across a large number of identical assets
- require personnel to work in far from shore, harsh weather condition locations.

Regular visual inspection of subsea assets will likely be required which, with the aim of eliminating the use of divers in floating wind, would likely be carried out by ROVs with crewed support vessels. ROVs launched from a USV and operated from shore can provide similar capability to carry out these inspection activities along with other tasks such as cathodic protection measurements and marine growth cleaning, if required. AUVs with sufficient navigation capability can also carry out inspection activities on subsea assets and present a significant potential use case when a large amount of identical assets are required to be inspected. Stakeholder discussions and offshore demonstrations [10] highlight this as a quickly developing area.

FOW Activity Review Summary

Table 2 provides a high-level summary of the conclusions from the FOW activity review for RAS application. While the scope of this project was to focus on FOW-specific activities, the results of the review highlighted the overlap between potential uses cases for floating and bottom fixed wind farm projects.

Table 2. Summary of FOW project use case areas.

Activity	FOW Specific	RAS	Comment
Pre-Construction Surveys			
Marine Life Surveys			Clear use cases for USVs and AUVs to carry out seabed surveys. USVs already being used to support survey scopes in offshore wind farms.
Geotechnical Surveys			
Geophysical Survey			
Wind Farm Installation Activities			
Export Cable Installation			Potential use cases to support installation activities through observation and post-installation survey tasks. Limited clear benefit compared to conventional ROV use.
Inter-Array Cable Installation			
Mooring System Installation			
Turbine Tow-Out and Hook-Up			
Operations & Maintenance Activities			
Substructure Inspection & Maintenance			Clear use cases to support subsea inspection and light intervention activities. Particularly appealing due the requirement for repetitive inspection of large numbers of identical assets in far from shore, harsh weather environments.
Turbine Inspection & Maintenance			
Array Cable Inspection & Maintenance			
Mooring System Inspection & Maintenance			

5 KEY CONSIDERATIONS FOR RAS APPLICATION

This section will focus on some key aspects of RAS application in FOW projects that were identified from the literature review and stakeholder engagement activities completed as part of this project. These considerations have been grouped into the following areas:

- Level of autonomy and human intervention.
- Communications and data transfer requirements.
- Operational requirements (including task duration and power requirements, task scope, operating weather limits, launch and recovery requirements, and impact of floating turbine motion).
- Regulatory requirements and considerations.

Level of Autonomy

Increased autonomy is becoming progressively important for most robotic systems, including subsurface vehicles, surface vessels and aerial vehicles. The RAS technologies presented in this report span a range of autonomy levels, with different corresponding requirements for human intervention.

At the lowest level, ROVs are completely operated by human pilots onshore or on the vessel. The pilot sees live video feed from the ROV and manually controls all of its movements and tasks. This allows for direct and precise control but requires continuous attention and is limited by communications bandwidth and latency over long distances when large amounts of data are required to be transferred. It can also be mentally taxing for pilots to directly control ROVs for long periods of time.

To reduce the requirement on pilots, semi-autonomous ROVs can perform some basic functions independently, such as automated piloting and navigation. However, for more complex tasks, the ROV still requires human supervision and input. The pilot is therefore able to focus on oversight and higher level decision making as the ROV covers inspection routes and terrain without constant input.

The highest level of autonomy, “supervised autonomy”, entails the ROV being able to carry out full missions and make decisions independently with little direct human control. The ROV uses advanced perception, planning, and control algorithms to inspect subsea assets, avoid hazards, and adapt to changing conditions. The role of the human supervisor is then focused more on mission planning, system monitoring, and occasional intervention if needed.

Regardless of autonomy-level, human operators will still be required to some extent. Humans can utilise intuition and contextual knowledge that the ROV lacks. Additionally, humans are better at improvisation and handling novel situations that the ROV's algorithms could not account for. Operator oversight also serves as a backup measure to make sure that the ROV's autonomous actions are aligned with the mission goals and safety standards.

There are a number of proposed definitions for level of autonomy and Table 3 provides an example of a level of autonomy definition for Maritime Autonomous Ship Systems (MASS). Regulations and industry standards impact permitted levels of autonomy; compliance, risk management, and liability considerations will impact the need for human supervision.

Table 3. Example of definition of levels of control autonomy for Maritime Autonomous Ship Systems (MASS) as given in the MASS UK Industry Conduct Principles and Code of Practice [11].

Level	Name	Description
0	Crewed	MASS is controlled by operators aboard
1	Operated	Under Operated control all cognitive functionality is within the human operator. The operator has direct contact with the MASS over e.g., continuous radio (R/C) and/or cable (e.g., tethered UUVs and ROVs). The operator makes all decisions, directs and controls all vehicle and mission functions.
2	Directed	Under Directed control some degree of reasoning and ability to respond is implemented into the MASS. It may sense the environment, report its state and suggest one or several actions. It may also suggest possible actions to the operator, such as e.g. prompting the operator for information or decisions. However, the authority to make decisions is with the operator. The MASS will act only if commanded and/or permitted to do so.
3	Delegated	The MASS is now authorised to execute some functions. It may sense environment, report its state and define actions and report its intention. The operator has the option to object to (veto) intentions declared by the MASS during a certain time, after which the MASS will act. The initiative emanates from the MASS and decision-making is shared between the operator and the MASS.
4	Monitored	The MASS will sense environment and report its state. The MASS defines actions, decides, acts and reports its action. The operator may monitor the events.
5	Autonomous	The MASS will sense environment, define possible actions, decide and act. The Crewless Vessel is afforded a maximum degree of independence and self-determination within the context of the system capabilities and limitations. Autonomous functions are invoked by the on-board systems at occasions decided by the same, without notifying any external units or operators.

Communications

A sufficient level of communication between the RAS technology and a human operator was highlighted repeatedly as a key requirement by stakeholders. The communication system needs to transfer data relating to navigation, vehicle monitoring, and recorded sensor measurements. Communication capabilities are impacted by the level of autonomy and environment conditions, where systems carrying out tasks autonomously could have lower data transfer and connectivity demands, especially as processing data prior to transmitting could reduce bandwidth requirements.

However, stakeholder engagement emphasised the importance of live, real-time data from remote inspections at an equivalent level of telepresence for remote inspectors. Live video during inspection tasks has the advantages of allowing inspectors to confirm the quality of data capture, identify potential issues and areas of interest in real time, subsequently responding during the ongoing inspection, potentially preventing the need to return to the asset again. Such high-quality streaming requires large amounts of data (and communications) transfer.

Increasing communication capabilities have been a focus point, especially for the application of remote sensors and digital twins, which require continuous transfer of large amounts of data. Working towards this in recent years, several large offshore wind farms have installed 4G networks at their sites [12], [13] and 5G networks are also beginning to be installed [14]. Environment can also impact communication capabilities; subsea data transfer, for example, between an untethered underwater vehicle and a surface vessel, is more challenging due to distance and bandwidth limitations on tether-less communications methods such as acoustic signals. Acoustic communications over long distances can be impacted by wave conditions and increase power consumption, making the removal of a surface vessel difficult. To mitigate environmental impacts,

some hovering AUV concepts still operate with fibre-optic tethers, allowing for real-time data transfer.

5.1.1 Regulatory requirements on communication

Regulations will impact communication requirements and design. The Workboat Code Edition 3 (discussed in more detail in Section 5.4) states some communication requirements for Remotely Operated Unmanned Vessels (ROUV), mainly related to the safe operation of remotely operated vehicles. Section 4.2 of the Code highlights importance of connectivity between the vessel and ROC. The requirement for a secondary communications system is also outlined, with the minimum ability to:

- Command the vessel to enter a safe state.
- Activate the emergency stop.
- Activate not-under-command lights.
- Receive and respond to critical alarms.

There are also requirements in the Code related to the cameras and sensors required for navigation. Additionally, Section 7 of the code outlines requirements for ROCs. It is also highlighted that the vessel owner/operator shall provide evidence, for example, that:

- “Latency and data bandwidth requirements will not exceed the connectivity capabilities in all intended weather conditions and distances from the Remote Operation Centre.”
- “Latency shall not result in an unsafe condition.”
- “Communications and control equipment is adequately protected from electromagnetic interference.”
- “Alarm and emergency data from the Remotely Operated Unmanned Vessel is correctly displayed and audible at the Remote Operation Centre.”
- “Connectivity and signal strength between a Remotely Operated Unmanned Vessel and Remote Operation Centre shall be monitored at a frequency appropriate to the nature of the vessel’s operation and communications equipment.”

Operational Requirements

Engagement with shareholders and work throughout this project highlighted five main requirements for efficient operation.

5.1.2 Duration Offshore

The long operational duration for technologies including ROVs, AUVs, USVs, and UAVs is a key factor for determining performance: longer offshore tasks require more power and network reliability. Additionally, long offshore periods introduce corrosion and biofouling risk for robotic systems.

To lengthen operational times, vessels may be tethered from a USV, dependent then on power from the USV. Tethers may also limit range from vessel and cause drag. Untethered ROVs require periodic

recovery for data acquisition, maintenance, and recharging, and UAV flight duration is restricted similarly by battery life and communication limitations. To increase operational duration, higher capacity power sources could be used. However, this benefit would need to be weighed against the additional payload mass.

5.1.3 Task Scope

Inspection and maintenance tasks will depend on the capabilities and limitations of technologies used, as well as the duration of activities and work scope. For instance, ROVs equipped with cameras, sonars, and manipulator arms can undertake remote operations including close visual inspections, ultrasonic testing, cleaning, grabbing samples, and light maintenance activities (large work-class ROVs can perform heavy intervention tasks). ROVs excel at underwater inspection, but face challenges operating near the sea surface.

UAVs are suited for inspecting large components above sea (e.g. turbine, platform topsides) using imagery and videography, providing visual overview of the infrastructure. However, most lack the ability to undergo interventions: small UAVs cannot carry heavy sensors and have short operational time, limiting inspection tasks.

5.1.4 Weather Limits

Significant wave height, current, wind speed, visibility, and precipitation can impact offshore deployment and data acquisition for RAS. Dense fog, icing, heavy rain, and fog can restrict operations, visual inspections, and positioning.

ROVs and AUVs are mainly limited by wave and current conditions, with most ROVs operating down to sea state 4 and a significant wave height between 2m-2.5m. Current limits for an observation class ROV are around 1 knot, increasing up to 3 knots for a work class ROV [15]. Limitations vary across technologies, generally increasing with size and thruster capability. Small UAVs have strict limits, operating only in light winds (up to 10-15 m/s) and moderate rain.

5.1.5 Launch and Recovery

Sea state, vessel stability, and positioning can affect deployment and recovery of subsea and aerial vehicles, with manual handling requiring significant planning and labour. Additionally, UAVs require clear deck space for launch and recovery, which may be limited offshore. Systems to improve these processes include stabilised platforms, dynamic positioning, and automated handling systems. Alternatively, some technologies can be deployed from shore or a sheltered location and transit to site, removing offshore launch and recovery limitations. This approach would then need to consider technology endurance and transit distance.

5.1.6 Floating Turbine Motion

The dynamic motion of a floating structure is an additional challenge for integrating robotic systems. Asset motion can impact navigation and position of RAS and impact collected data such as videos and 3D reconstruction. Currently, wind farm operators state that UAVs need to maintain a distance of 10m from any wind turbine, which may become more challenging with floating assets. High frequency large amplitude motion of floating assets would also likely present challenges for operator controlled subsea inspection vehicles; in the longer term, advanced autonomous navigation systems may be better equipped to respond to such motions than human operators.

The impact of motion on substructures and mooring lines was specifically highlighted by supply chain stakeholders, as the limits are not well defined. Further clarity around inspection requirements would support development of RAS technologies for application in FOW.

Regulatory Requirements

Due to the fast rate at which RAS is developing and advancing, there is a lack of specific guidance and regulation in place for these technologies. In the ORE Catapult's extensive experience within the area of robotics and autonomous systems, regulation is regularly highlighted as one of the key challenges for the adoption of RAS in offshore wind. This section provides a brief summary of the key Regulatory Bodies in the UK.

5.1.7 Marine Regulation

The two primary regulatory bodies for marine activities in the UK are the International Maritime Organization (IMO) and the Marine and Coastguard Agency (MCA).

'The International Maritime Organization (IMO) is the United Nations (UN) specialised agency and the global standard-setting authority for the safety and environmental performance of international shipping.' [16].

The Maritime & Coastguard Agency (MCA) within DfT has the responsibility for the implementation of maritime legislation and guidance [16]. Therefore, international standards are set by the IMO and these are implemented into UK legislation and guidance by the MCA. For a remotely operated or autonomous vessel to operate in the UK, approval from the MCA is required.

In September 2023, the MCA published MGN 664 (M+F) Amendment 1: Certification process for vessels using innovative technology [17]. This document: *'provides updated guidance on how to process an application for the certification of UK vessels wherever they may be, or other vessels operating in UK waters that use Innovative Technology or where a risk-based approach is used.'*

In 2022, the MCA also produced an updated Draft version of the Workboat Code Edition 3: The Safety of Small Workboats and Pilot Boats – A Code of Practice [18] for public consultation. This is applicable to vessels below 24m and includes *'mandatory requirements that apply to workboats, including remotely operated unmanned vessels (ROUVs)',* where ROUVs are *'vessels with no persons on board, where the vessel is operated from a Remote Operation Centre.'*

Annex 2 of the Workboat Code Edition 3 outlines the additional requirements the ROUVs shall comply with, with sections focused on:

- Bilge Pumping, Fire Appliances and Alarms.
- Connectivity, Pre-Departure Checks and Responding to Distress.
- Navigational and Anchoring Equipment.
- Personnel Health, Safety and Medical Care.
- Remote Control of Remotely Operated Unmanned Vessels.
- Safety Management System and Contingency Measures.

It is stated that *"Vessel owners/operators wishing to operate a Remotely Operated Unmanned Vessel which is not able to meet the requirements of this Annex and Code may be considered on a case-by-*

case basis by the Administration.” It also outlines sections of the main code which are not applicable for ROUVs.

In November 2020, Maritime UK published the ‘Maritime Autonomous Ship Systems (MASS) UK Industry Conduct Principles and Code of Practice’ [11]. The aim of this document is to *‘establish practical guidance, standards, and best practice for those who design, build, manufacture (including testing and commissioning), own, operate and control autonomous and semi-autonomous MASS primarily less than 24m. It will also establish some principles and guidance which will be applicable for those operating larger MASS (...)*’.

Regarding underwater remotely or autonomously operated vehicles, there is less guidance available. In September 2021, the Department for Transport launched a public consultation on ‘Future of transport regulatory review: maritime autonomy and remote operations’ [19]. One of the points of consultation was whether there should be the creation of power to regulate autonomous and unmanned submersible apparatus in a manner consistent with manned submersible apparatus. The Government Response was published in September 2023 [19], in which the outcome given is that the Government intends for Primary Legislation to include a power to regulate autonomous and unmanned submersible apparatus, to allow more detailed regulations to be developed in the future.

Therefore, although there is regulation and guidance available around remote and autonomous technologies operating offshore in the UK, this is variable depending on the technology and is still continuously being developed at a rate slower than the technology is advancing. A repeated concern from offshore wind developers and supply chain stakeholders was the lack of regulation for robotics operating in offshore wind farms and no current clear consensus on RAS regulation, as well as lack of regulatory framework for unmanned vessels.

5.1.8 Aerial Regulation

There are two key Regulatory Bodies relevant to the UK: the International Civil Aviation Organisation (ICAO) and the Civil Aviation Authority (CAA). Unmanned aerial systems within the UK are regulated under two legislative frameworks - regulations within the framework of UK Regulation (EU) 2018/1139 (the Basic regulation) and The Air Navigation Order 2016, as amended, within the framework of the Civil Aviation Act 1982 [20]. The primary UAS guidance document is CAP722 [20], which outlines the general operational requirements for operating unmanned aerial vehicles in the UK, which are applicable to all types of operation. For the application of RAS, the sections of most interest are those focused on Beyond Visual Line of Sight (BVLOS) (where the operator cannot directly see the asset) requirements and Autonomy and Automation.

Section 4.5 of CAP 722 outlines the CAA’s general interpretations around autonomy and level of authority and it is stated that ‘The general principle to be observed is that all UAS must be under the command of a remote pilot’.

Similar to marine regulation, aviation regulation is undergoing ongoing development to adapt to technology development and future requirements. The CAA is currently working on their regulatory frameworks and certification to *‘enable the next generation of aircraft to be developed and operated in UK airspace and continue to extend the use of drones...’* [21]. In August 2023, an industry update was published [22]. This highlights that the CAA are already providing authorisations for BVLOS operations, but are working toward enabling ‘scalable, routine BVLOS flying’ through its DiSCO Programme. In April 2023, the ‘policy concept’ document CAP 2533 Airspace Policy Concept: Airspace Requirements for the Integration of Beyond Visual Line of Sight Unmanned Aircraft was published which aims ‘to present an airspace policy concept that describes a pathway forward to deliver that integration [of UAS operating beyond visual line of sight within the airspace system]’ [23].

Regulation for aerial systems was highlighted by Stakeholders as a challenge for remote and autonomous systems in floating wind, including a required safety case for BVLOS operation.

6 POTENTIAL BENEFITS OF RAS APPLICATION IN FLOATING WIND

The adoption of RAS in floating offshore wind will be based on the development of a suitable business case for the wind farm operator. This section will outline the potential benefits from the use of RAS on a floating offshore wind at a qualitative level based on the literature review and stakeholder engagement. This will be focused on the following areas:

- Reduced cost through cheaper vessels and operational efficiencies.
- Health and safety benefits through removing personnel from the offshore environment.
- Emissions reduction through using smaller, more fuel-efficient technologies.

Reduced Cost

There are several potential routes to reducing the cost of floating offshore wind farms through the application of RAS. These include:

- The use of lower cost vessels and technologies, compared to conventional approaches, to carry out activities.
- Operational efficiencies which ultimately reduce the overall cost of a specific activity or series of activities (for example reduced activity duration, increased operating envelope, etc.).
- Enabling improved long-term asset management approaches which ultimately reduce the cost of activities over the lifetime of the wind farm (for example evidence-based maintenance planning).

Currently, during the development phase of an offshore wind farm, large survey vessels are used to carry out geophysical surveys using sensors such as multi-beam echosounders, side-scan sonar, and sub-bottom profilers. Likewise, when carrying out subsea inspection and O&M activities on floating wind farms, a support vessel will likely be required. These large vessels are associated with high costs; geophysical surveys have an estimated cost around £700k for a 1GW wind farm [24] and ROVSV day rates are estimated to be around £50k/day. The use of smaller, uncrewed vessels can have lower equivalent day rates, dependant on the technologies used and their corresponding capability. Commercial costs for RAS are difficult to estimate, however through stakeholder discussions and previous work completed in ORE Catapult, it is generally expected that the cost of using an uncrewed surface vessel will be lower than a large offshore survey vessel. Any cost comparison will also be dependent on the strategy used.

Cost reduction can also be achieved through improving offshore activity efficiency, such as expanding operational conditions and shortening activity time. Stakeholder engagement identified key improvement opportunities. This included RAS's potential to expedite and improve the quality of inspections, especially repetitive inspections of subsea assets. Additionally, the use of autonomous technologies increases the potential for activities to be carried out in parallel, with multiple systems deployed simultaneously, allowing for significant reductions in project duration without large cost increases from using multiple support vessels. However, data transfer requirements should be

considered, especially for tether-free operations. Section 8 of this report investigates the multi-system method in more detail.

Another route for cost reduction is enabling an evidence-based approach to asset management through the use of relatively low cost and easily deployed inspection systems. These provide more frequent, opportunistic inspections, increasing the amount and frequency of data. Inspections can be carried out concurrently to maintenance activities on the turbine or in the area. Combining regular autonomous inspection with highly efficient data processing, such as systems that produce high-quality 3D asset models, improves the understanding of asset condition over time.

Health and Safety Benefits

The potential health and safety benefits associated with the application of RAS is generally focused on removing personnel from the offshore environment and moving them onshore. There is a clear consensus that human divers should be avoided during subsea inspection and maintenance activities for floating wind. The risk associated with activities such as blade inspections using rope access technicians is also increased in the environmental conditions expected at floating wind farm sites. Various methods can complete these activities, including human-operated ROVs from conventional support vessels and aerial drones operated from a vessel near the turbine. However, the application of remotely controlled robotic systems from shore can potentially eliminate the need for personnel offshore completely when carrying out these and other tasks.

Emissions Reduction

Potential emission reductions can be achieved when using smaller, more efficient vessels to carry out inspection tasks. These technologies can either displace larger, higher-emission, vessels completely, or permit offshore activities to be completed more efficiently, reducing the time that larger vessels are offshore and emitting greenhouse gases. As an example, when Fugro completed remotely operated survey and inspection of the Aberdeen offshore wind farm using a USV with electric ROV, they reported a reduction in fuel consumption by up to 95% compared to conventional vessels [25]. Other technologies claim potential emission reductions of a similar magnitude.

7 CURRENT CHALLENGES FOR RAS APPLICATION IN OFFSHORE WIND AND POTENTIAL ENABLERS

Through the Stakeholder Engagement Process carried out as part of this project, both offshore wind developers and the supply chain identified clear potential benefits for floating wind. However, there are still a range of challenges that face both RAS technology developers and service providers, and wind farm operators in the application of these technologies. This section will outline some of the challenges identified as part of this project before going on to outline some of the potential enablers also identified.

Operational Challenges

Four challenges surrounding the operation and technical aspects of RAS application were highlighted:

1. **Communications and data transfer** A consistent concern is the requirement for reliable communications to enable effective RAS application; the specifics will vary for the system being used, but communications and data transfer requirements across all wind farm

activities should be considered in early stages of project development and implemented into the project scope. This could include any data requirements for sensors, digital twins, etc.

2. **Clear understanding and alignment on floating wind use cases and drivers** There is a demand for offshore wind developers to develop a clear understanding of the use case requirements and expectations for robotics and autonomous systems on floating offshore wind farms; both technology developers and operators, and the offshore wind developers would benefit from clear floating wind problem statements, open discussions on the current state of RAS technology and agreed understanding of unique challenges faced by floating wind.
3. **Practical considerations: power, charging requirements, and range** Currently, there are limitations around charging and the range of remote and autonomous technologies. This was specifically mentioned for AUVs.
4. **Autonomous navigation around assets** Navigation and localisation of vehicles in the subsea environment, particularly when navigating around floating wind infrastructure such as mooring lines and substructures was a highlighted challenge. Integrated sensors, such as SPRINT-Nav [26], can enable accurate positioning required for six degree of freedom navigation.

Non-Technical Challenges

Five barriers to implementation outside of technical challenges were highlighted:

1. **Regulation** A review of current UK regulation is covered in Section 5.4. However, key challenges raised during stakeholder engagement highlighted the lack of a clear route or framework for RAS (especially autonomous systems) approval.
2. **Trust and risk appetite** There is a hesitancy in applying new technologies and approaches in offshore wind, particularly the application of RAS. Continued engagement and successful demonstration of technologies is key to build trust and confidence.
3. **Limited testing and demonstration opportunities** Currently, there are limited opportunities for the testing and demonstration of technologies. Novel technologies will therefore find it challenging to progress their TRL.
4. **Workforce skills gaps** As an industry adopts new technologies and techniques, a requirement develops for new skillsets and knowledge. There will likely be a skills gap across the industry for people with knowledge of technologies that underpin RAS operations
5. **Clear business case** New technologies must be competitive with existing approaches. Therefore, there has to be more understanding of both a) what combination of systems are the most appropriate to carry out different tasks, and b) the point at which these systems become financially and technically appealing.

Potential Solutions

Three potential solutions to these challenges were identified to support RAS development and implementation:

1. **Continued collaboration and engagement between developers and the supply chain to provide market clarity and direction.** Ongoing discussions are necessary to address

challenges; these would provide clarity to the market and areas of development, allowing the supply chain to adapt to specific market needs and address current blockers.

2. **Opportunities for technology testing and demonstration.** Currently there are limits for technology testing and demonstration; an area which ORE Catapult have been trying to address. This year, both the ORE Catapult Digital, Autonomous and Robotics Engineering (DARE) Centre in Blyth and the ORE Catapult 5G Testbed at Grimsby Port and Lynn and Inner Dowsing Wind Farm have been opened. These facilities should improve access to facilities for testing of robotic and smart O&M technologies.
3. **Workforce upskilling.** Continued upskilling of people within the offshore wind industry to better equip developers, operators, and other stakeholders to work with remote and autonomous technologies and the wider systems which support them is required to address the skills gap. Additionally, collaboration between industry and academia is a potential way to help knowledge transfer.

8 CASE STUDY: INSPECTION OF FOW SUBSEA COMPONENTS

Based on the review of floating offshore wind activities, a cost modelling exercise of scheduled inspection of floating turbine subsea components was performed to investigate the potential benefits of RAS application. Inspection of subsea components presents a highly FOW-specific use case of RAS due to a) subsea components that are unique to floating wind farm projects, and b) the large quantity of subsea assets across a wind farm compared to oil and gas projects. It also presents a use case which is being targeted by ROVs and AUVs currently available or in development.

Background and Conventional Approach

Due to limited operational experience, there is challenge in defining a ‘conventional approach’ to FOW subsea inspection. Subsea inspections of the five Hywind Scotland turbines were carried out over a 10 day period using a work-class ROV and support vessel [27]. Subsea inspection of the FloatGen turbine trialled the use of an autonomously controlled ROV launched from a CTV to inspection mooring line and dynamic cable integrity over a three day period [28].

As part of the FOW Centre of Excellence PR37 Project (FOW O&M – Requirements and Cost Model), the baseline approach modelled for a commercial-scale floating offshore wind farm is to inspect subsea components for 20% of the turbines every year using an ROVSV with work-class ROV. The key modelling assumptions and results from the PR37 analysis are shown for reference in Table 4, with summer inspection campaign duration and cost shown in Figure 1 and Figure 2.

Table 4. Baseline modelling assumptions for conventional subsea inspection.

Parameter	Value
Case Study Site	North-East Scotland, 100 x 15MW turbines
Inspection Duration per Turbine (Hrs)	58
Operational Limits – Hs (m)	2
ROVSV Max Duration Offshore (Weeks)	2
Assumptions	Only one ROV is used per ROVSV; The impact of current speed on ROV operability is not considered; When multiple ROVSVs are used, all vessels are chartered until the final inspection is complete.

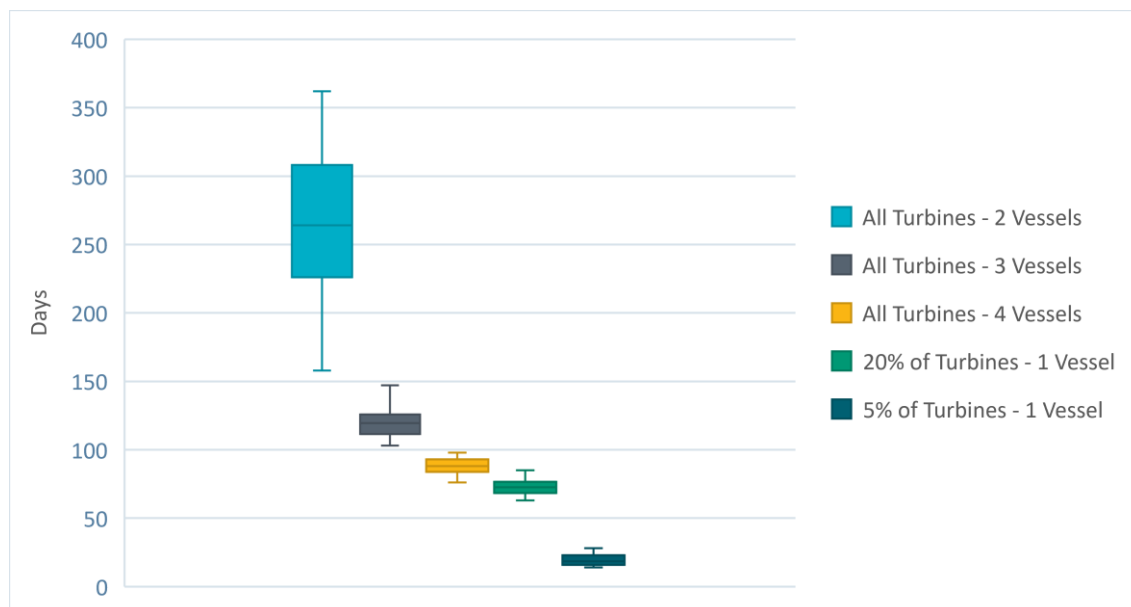


Figure 1. Box-plot of subsea inspection campaign durations based on twenty simulations of each scenario at Case Study Location 1 - NE Scotland.

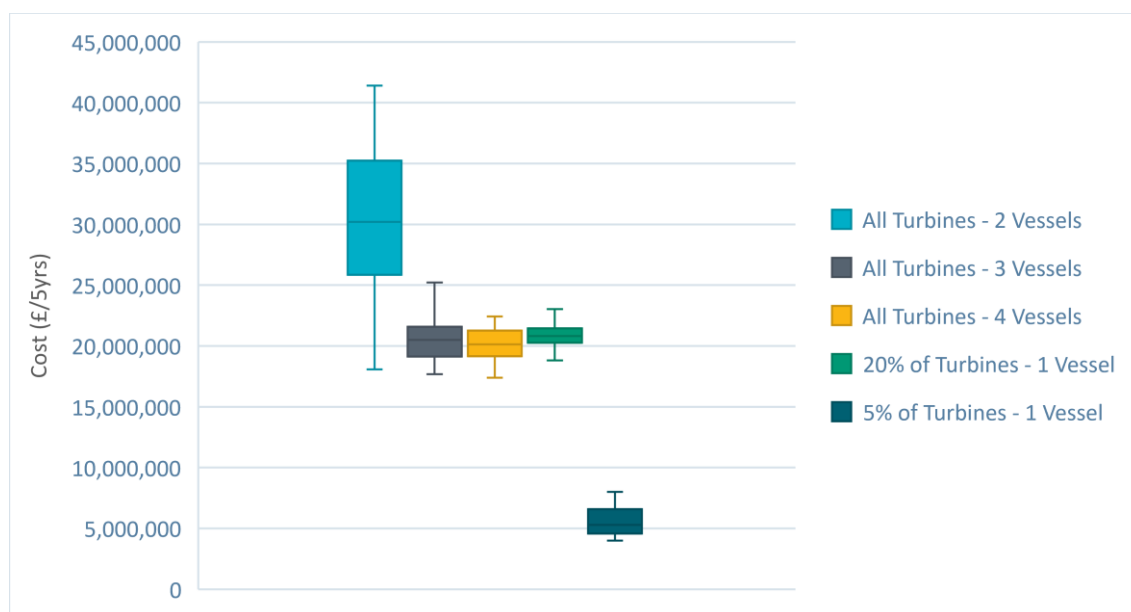


Figure 2. Box-plot of subsea inspection campaign total costs over a five-year period based on twenty simulations of each scenario at Case Study Location 1 - NE Scotland.

RAS Case Study Scenarios

8.1.1 Case Study Details

There were two specific scenarios assessed:

Scenario 1: Remotely operated USV with ROV

This is a theoretical scenario where an uncrewed surface vessel with an ROV, launched from shore, is used to carry out subsea inspection on wind farm subsea assets. This approach assumes a tethered ROV launched from a USV, differing from the conventional approach as all personnel (8 members) are assumed to be onshore.

Scenario 2: Crewed Vessel + Multiple AUVs

This is a theoretical scenario intended to represent a crewed offshore support vessel with ROV which can also simultaneously deploy multiple hovering AUVs or hybrid ROVs with autonomous navigation capability to carry out subsea inspection activities on wind farm subsea assets. It is assumed that two AUVs would carry out the initial inspection of the subsea components. A conventional, tethered ROV is then deployed afterwards to carry out required light intervention activities.

8.1.2 Case Study Results

Scenario 1: Remotely operated USV + ROV

It was found that the campaign duration is generally longer for the remotely operated USV with ROV scenario. This difference is driven by a combination of the assumed limited endurance time offshore and the lower transit speed compared to the conventional approach.

Figure 2 compares the estimated cost of subsea inspection campaigns over a five-year period using what has been defined as the conventional approach, against an approach where subsea inspection is carried out by the USV with ROV.

A key difference between Scenario 1 and the conventional approach is the removal of personnel from the offshore environment, with remote operations and data analysis being carried out onshore. Based on the campaign durations and the assumed ROV crew of 8 personnel, the median value of person days offshore saved in Scenario 1 is 636 days/year.

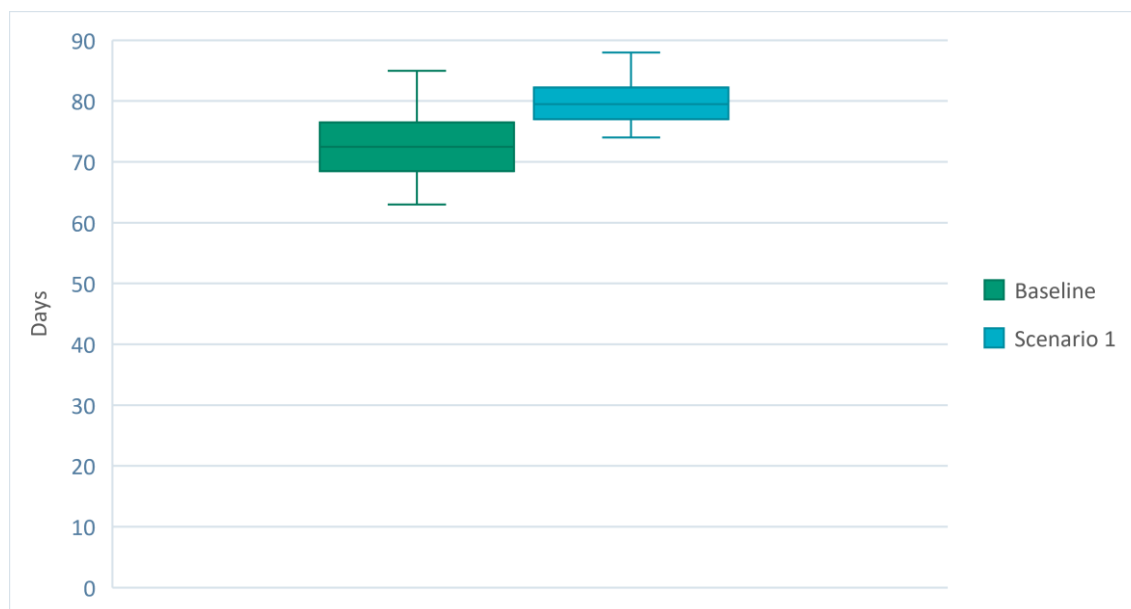


Figure 3. Box-plot of subsea inspection campaign duration based on twenty simulations at Case Study Location 1 - NE Scotland comparing the baseline inspection approach to an approach carried out using USV with ROV.

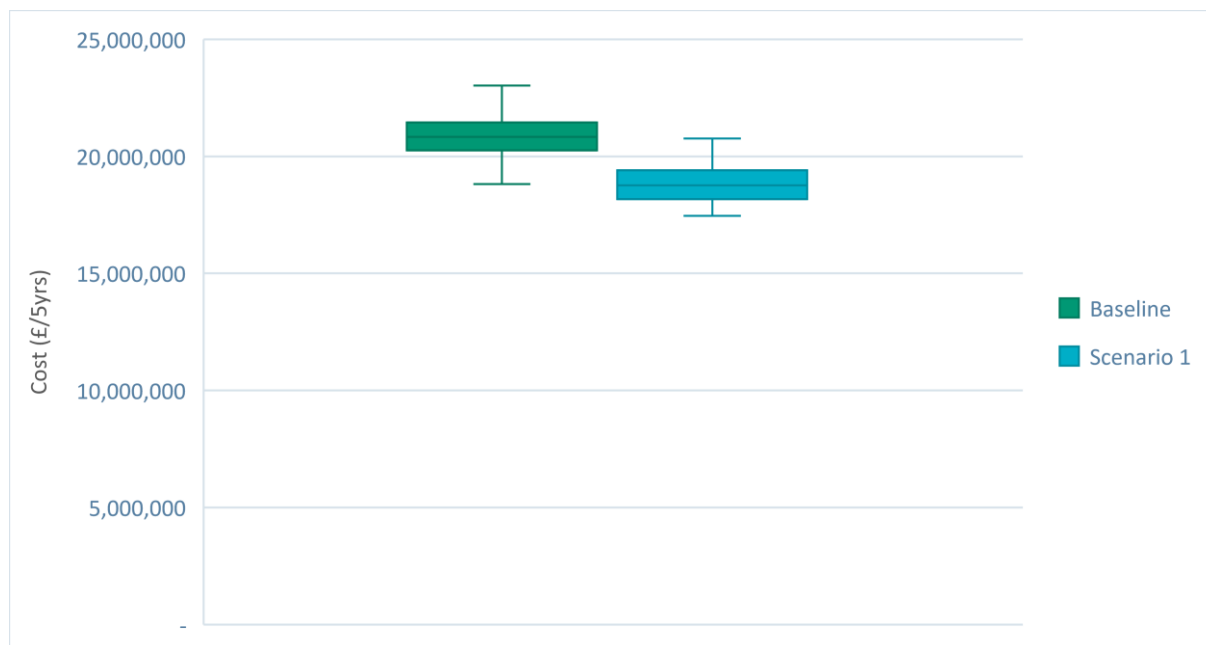


Figure 4. Box-plot of subsea inspection campaign total costs over a five-year period based on twenty simulations at Case Study Location 1 - NE Scotland comparing the baseline inspection approach to an approach carried out using USV with ROV.

Scenario 2: Crewed Vessel + Multiple AUVs

Figure 5 compares the campaign duration to carry out the inspection of subsea assets for 20% of turbines in a large, NE Scotland wind farm scenario using the 'conventional approach' against an approach where subsea inspection is supported by multiple autonomous underwater vehicles assumed to have hovering, or six degrees of freedom, navigation. It was found that the campaign duration was reduced by a large amount, the difference driven by the reduced activity duration in this scenario based on the assumption that multiple AUVs can quickly complete an initial inspection of subsea components in parallel, with the ROV carrying out a reduced scope of work on selected areas.

Figure 6 compares the estimated cost of subsea inspection campaigns over a five-year period using what has been defined as the conventional approach, against an approach where subsea inspection is supported by multiple autonomous vehicles. The cost difference is driven by the shorter campaign durations required in the AUV-supported inspection scenario. A large contributor to this cost is the assumption that an offshore support vessel and ROV are still required. It is assumed that this is still needed to a) provide communications and external positioning to the AUVs, b) provide charging for the AUVs, and c) allow light intervention activities to be carried out by an ROV. Going forward, there may be other ways to meet these needs.

The basis of the scenario investigated here is that the inspection of each turbine's subsea assets includes initial AUV survey followed by ROV tasks and reduces the overall duration of inspection for each turbine and subsequently campaign duration and cost. However, real-time data transfer from untethered AUVs is currently still a limitation of current acoustic subsea communications methods.

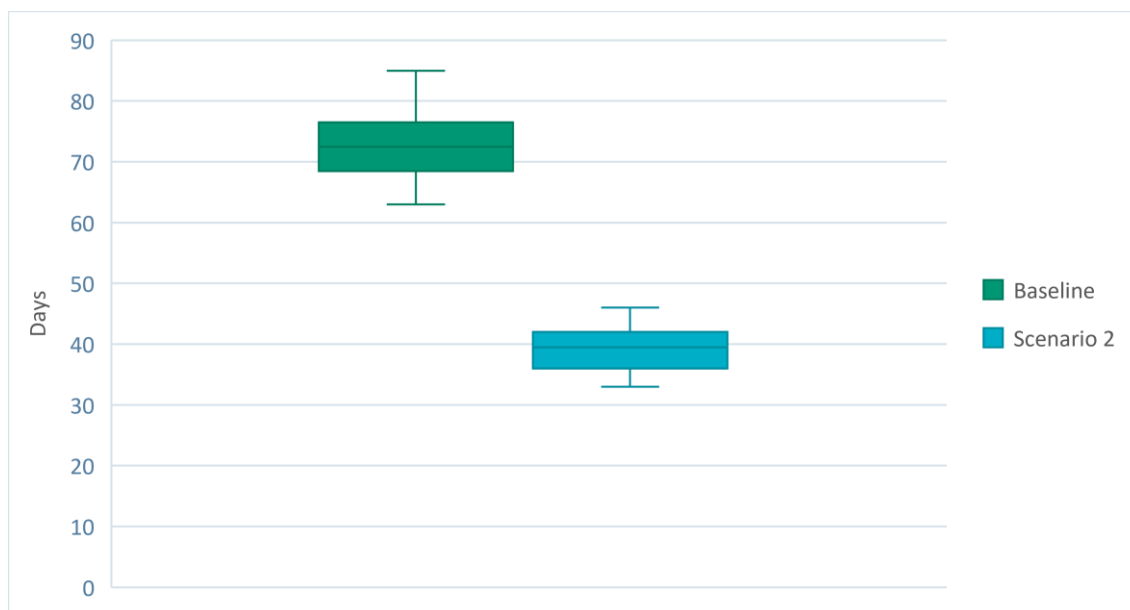


Figure 5. Box-plot of subsea inspection campaign duration based on twenty simulations at Case Study Location 1 - NE Scotland comparing the baseline inspection approach to an approach supported by AUVs.

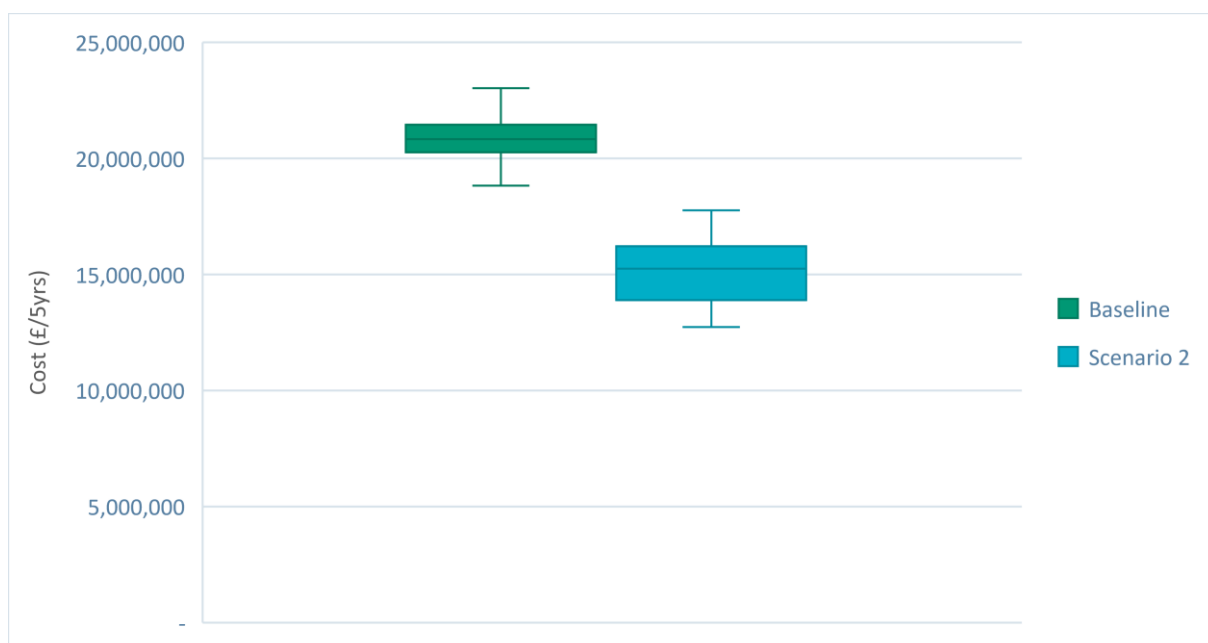


Figure 6. Box-plot of subsea inspection campaign total costs over a five-year period based on twenty simulations at Case Study Location 1 - NE Scotland comparing the baseline inspection approach to an approach supported by AUVs.

9 OVERALL CONCLUSIONS

As floating offshore wind farms begin to be installed further offshore and in harsher wave and wind conditions, the use of remotely operated and autonomous technologies present an opportunity to reduce the reliance on human personnel offshore. However, there is still a range of uncertainties associated with the widespread adoption of remotely operated and autonomous systems on floating offshore wind projects.

The overall objectives were 1) understand which floating wind project activities could present suitable use cases for RAS application, 2) what remote and autonomous technologies currently exist which could be used on floating offshore wind projects and what are some key considerations when using these, and 3) what are the potential impacts and benefits of using RAS compared to conventional methodologies. The findings from this work were produced through literature review, ORE Catapult internal knowledge, stakeholder engagement questionnaires and interviews, and internal modelling tools.

First, a representative overview of different remote and autonomous technologies was provided, including key characteristics of uncrewed surface vessels, subsea remotely operated vehicles, autonomous underwater vehicles, and uncrewed aerial vehicles. The key use cases for RAS on a floating offshore wind farm project were identified; this included seabed surveying and inspection of subsea assets such as moorings, substructures and cables. Tasks which are highly repetitive generally present a good use case for autonomous systems.

Potential benefits that could be achieved through the appropriate application of RAS in floating offshore wind projects were found to include reduced cost, improved health and safety through reduction or removal of personnel offshore, and reduced vessel emissions through the use of smaller, more efficient technologies. The use of robotics and autonomous systems present opportunities to carry out offshore activities more efficiently and with reduced human intervention compared to conventional approaches.

A number of key challenges for RAS application for floating wind were then considered, with discussion informed by stakeholder engagement activities. Challenges included different levels of autonomy and human intervention, communications and data transfer requirements, operational requirements, and regulation. There was broad consensus across stakeholders that some level of operator supervision is likely to be required in the foreseeable future. Communications and data transfer were also highlighted across stakeholder engagement activities as a key consideration for RAS application, particularly highlighting potential challenges with transferring large quantities of inspection data in real time. Communications and data transfer requirements for a new wind farm project should be evaluated at a holistic level as early as possible as part of project design and planning.

Finally, the estimated duration and cost of two floating wind subsea inspection campaign case study scenarios were modelled and compared to a baseline approach of inspection campaigns using a conventional tethered ROV with support vessel. Scenario 1, which considered replacing offshore vessels with a USV found slightly increased campaign durations and slightly lower cost compared to the conventional approach. However, a key difference was the reduction in personnel time offshore, with an estimated 636 personnel days per year moved from offshore to onshore. Scenario 2, which considered the deployment of multiple UAVs in parallel to perform inspections, led to a significantly reduced campaign duration, subsequently reducing the campaign cost. Note that specific input technical and cost parameters, and therefore results, will be dependent on specific technologies and

their capability. However, these case studies highlight the potential scope for the potential time and cost savings from more efficient operations.

10 RECOMMENDATIONS AND FUTURE WORK

Continued discussion and engagement across industry stakeholders:

This work identified a clear need from the supply chain to have continued engagement with the offshore wind developers and operators, including explicit points for alignment and agreement across the industry:

- FOW specific scopes of work (for example: what components must be inspected, what is the extent of the inspection, how often is this required, etc.);
- FOW operational requirements (for example: what is the extent of component motion, is real-time video footage a requirement, etc.);
- Business case drivers (what are the priority factors in business case development – cost, health and safety benefits, emissions reduction, etc.).

Increased testing and demonstration opportunities for technologies:

Throughout the stakeholder engagement process, two complimentary themes were highlighted:

- A wider lack of trust in remote and autonomous technologies across the industry.
- A lack of opportunities for technology developers to test and demonstrate technologies in representative environments and conditions.

Opportunities for testing and demonstration are therefore require to build confidence in RAS technologies. To facilitate this, the ORE Catapult Digital, Autonomous and Robotics Engineering (DARE) Centre opened in Blyth earlier this year and the ORE Catapult 5G Testbed at Grimsby Port and Lynn and Inner Dowsing Wind Farm was also opened this year.

Development of FOW inspection and maintenance reference scopes

Another potential piece of future work could be to develop FOW-specific reference inspection and maintenance scopes or sets of requirements that can be used to inform the wider industry of the likely needs and requirements for floating wind projects. This could be focused on a specific component such as the mooring system or the substructure and would provide a reference for both the developers and the supply chain to clearly understand specific use cases for RAS technologies.

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