REMOTE TECHNOLOGY STUDY

Remote Technology for Offshore Wind Inspection and Maintenance

Bureau of Safety and Environmental Enforcement

Document No.: 10311530-HOU-R-01
Issue: C, **Status:** FINAL
Date: 28 August 2022

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ACKNOWLEDGMENT OF SPONSORSHIP

Study concept, oversight, and funding were provided by the US Department of the Interior, Bureau of Ocean Energy Management, Environmental Studies Program, Washington, DC under Purchase Order Number 140E0121P0021.

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Date of issue:	28 August 2022	
Project No.:	10311530	
Proposal Reference:	214493-HOU-P-01-A	
Document No.:	10311530-HOU-R-01	
Issue/Status:	C/FINAL	

Task and objective:
This report presents the results of the remote inspection technology assessment conducted by DNV on behalf of the Bureau of Safety and Environmental Enforcement.

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☐ Strictly Confidential	For disclosure only to named individuals within the Customer's organization.	Keywords:
☐ Private and Confidential	For disclosure only to individuals directly concerned with the subject matter of the document within the Customer's organization.	remote technology, offshore wind monitor, inspect, test, repair, replace
☐ Commercial in Confidence	Not to be disclosed outside the Customer's organization.	maintenance, automation, robotics
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Issue	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	1 July 2022	Draft, initial release	Ruth H. Marsh Idalia Machuca Anna Brzozowski	Jake Frye	Dayton Griffin
B	17 August 2022	FINAL DRAFT	Ruth H Marsh Anna Brzozowski	Jake Frye	Jake Frye
C	28 August 2022	FINAL ISSUE	Ruth H. Marsh	Jake Frye	Jake Frye

Table of contents

Appendices

List of tables

List of figures

List of abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
AUV	Autonomous Underwater Vehicle [1]
AWL	Above water line. Generally, all equipment that spends the majority of the time above the surface of the water
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
BWL	Below water line, Generally, all equipment that spends the majority of the time below the surface of the water
CFR	Code of Federal Regulations
CMS	Condition Monitoring System
CRISP	Cross-industry standard process
DNV	DNV Energy USA Inc.
DT	Digital Twin
DTMS	Distributed temperature measurement system
EASA	European Union Aviation Safety Agency
HAT	Highest astronomical tide. Highest water level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions.
LAT	Lowest astronomical tide. Lowest water level that can be expected to occur under average meteorological conditions and under any combination of astronomical conditions.
IMU	Inertial Measurement Init: a device that can measure and report specific force and angular rate of an object to which it is attached. Comprised of a gyroscope, accelerometers, magnetometer.
INU	Inertial Navigation Unit: a device used below the surface (where GPS does not work) to calculate by dead reckoning the position, orientation, and velocity of a moving object to which it is attached. Equipment includes a computer, accelerometers, gyroscopes. Use of an underwater acoustic positioning system (echo-location) can improve accuracy.
IR	Infrared radiation
ML	Machine Learning – an aspect of AI involving the design, study, and development of algorithms that permit machines to learn without human intervention
MPI	Magnetic particle inspection
NDT	Non-Destructive Testing
OCS	Outer Continental Shelf
OSS	Offshore Substation (also referred to as Electrical Service Station or Offshore Service Platform)
RBI	Risk-Based Inspection
RIT	Remote Inspection Technology
RNA	Rotor nacelle assembly
ROV	Remotely operated vehicle
RT	Remote Technology, including for monitoring, inspection, testing, maintenance, repair
SF	Safety Factor
Splash Zone	Area of an offshore asset positioned between LAT and HAT, which experiences atmospheric and immersion-type corrosion as well as abrasion and impact damage in areas around boat landings.
UAV, UAS	Unmanned aerial vehicles [2], unmanned aerial systems
USV	Uncrewed (Unmanned) Surface Vessels

UUV	Uncrewed (Unmanned) Underwater Vehicle
UT	Ultrasonic Testing
WTG	Wind Turbine Generator

EXECUTIVE SUMMARY

This report provides a guide to the current state of remote technology (RT) as applied to maintenance of offshore wind farms. The purpose of this study was to evaluate the available options for conducting remote activities such as monitoring, inspection, testing, maintenance, repairs and replacements on offshore wind farm components and subsystems including turbines, offshore substations, foundations or mooring systems, electrical cabling, and other offshore wind farm components, both above and below the water line.

Remote technology review

The technology review was organized around nine focus areas, with the results collated in a series of registers, one register for each focus area. The nine registers, collected in an Excel workbook accompanying this report as well as provided in Appendix A, cover the topics of remote monitoring methods, commercially available technology that can be used for inspection as well as other tasks (maintenance, testing, repair, replacement), a list of components that can be inspected, inspection programs and intervals, a summary of industry standards that can be met using remote technology, future capabilities under development, and best practices for data-handling and documenting the results of remote technology maintenance campaigns. Together these reviews provide a comprehensive survey of current and future capabilities of remote technology to serve the offshore wind industry in the United States (U.S.).

Summary of results

This study included a qualitative assessment of potential economic benefits of RTs. RTs can provide significant economic benefits through operation cost savings, time savings, reduction of risk to personnel, and early failure detection. Providers of drone-based blade inspections and maintenance report operational cost savings of between 35% and 80% compared to manual when conducting blade inspection, cleaning, and lightning protection system testing. Cost savings of up to 50% in blade defect marking and categorization are reported. Unmanned underwater vehicles featuring non-destructive inspection capabilities reduce the need for technicians to access difficult locations, and are able to operate in harsher environments than can humans, which in turn reduces costs and allows for a lower frequency of inspection.

The regulatory framework concerning remote technologies is still evolving and varies for different technologies. In the U.S., drones flown for commercial purposes up to 55 pounds are regulated by the Federal Aviation Administration (FAA) to ensure they are flown by certified pilots. As yet there are no FAA regulations permitting operation of larger drones for commercial or recreational use. Furthermore, FAA jurisdiction is limited to 12 nautical miles (nm) offshore. Since most offshore wind project areas fall beyond 12 nm offshore, “rules of the road” may need to be developed for drones operating beyond FAA’s direct jurisdiction. For other types of robots such as crawlers, robotic arms, fully autonomous mobile robots, etc., innovation is currently the driving factor. As solutions mature, a move toward standardization of infrastructure could help increase their utility, contributing to reducing the overall cost of offshore wind. The right regulatory framework (e.g., performance-based), would likely be needed to drive standardization of both wind farm equipment as well as remote technologies for maintaining wind farms. Such standardization could benefit of the entire US offshore wind industry.

There is generally very little regulatory framework pertaining specifically to unmanned underwater vehicles (UUV), so operators are left to fill the gaps using existing maritime law and federal statutes. This points to the need for further development of UUV-specific rules for the benefit of the entire offshore wind industry.

Summary of conclusions

Key conclusions are summarized below:

- The landscape of remote technologies is changing rapidly, with significant innovation occurring in two specific areas: miniaturization of sensors and increasing application of data science principles to the processing of remote technology data. DNV has identified data mining (the process of extracting useful information from very large data sets) and machine learning (an aspect of artificial intelligence involving the design, study, and development of algorithms that permit machines to learn without human intervention) as key developments within the field of data science that will increase the effectiveness and utility of remote technologies.
- There is strong evidence that deploying remote technology for offshore wind operations and maintenance will not only increase safety by reducing the need for technicians to work offshore but will reduce costs, potentially significantly. For example, savings of 35% in operational costs and 50% in marking/categorizing defects have been reported for rotor blade inspections using drones.
- As yet very few remote vehicles are actually fully autonomous and capable of being deployed from shore, the turbine platform, or an underwater charging station. Most are deployed from a vessel in conjunction with technicians trained to operate the remote devices and carry out tasks the remote equipment cannot.
- Gaps remain in the regulatory framework for remote technologies related to offshore wind. While the FAA sets requirements for small drones (up to 55 lbs) operating out to 12 nm from shore, there are few regulations governing drones in international airspace or other types of robots that operate above the waterline. Below the water line, there is very little regulatory framework pertaining specifically to UUVs, which are expected to increase in number significantly as more offshore wind projects are built in US waters

1 INTRODUCTION

The Bureau of Safety and Environmental Enforcement (BSEE) retained DNV Energy USA Inc. (DNV) to conduct a study of surveying remote technologies (RTs) that either are currently-available or will in the future be able to execute remote monitoring, inspection, repair, and/or replacement of offshore wind turbine components, or carry out other maintenance activities remotely. This report presents the results of DNV's analysis.

1.1 Objective and scope of remote technology review

This report provides a guide to the current state of remote technology (RT) as applied to maintenance of offshore wind farms. The purpose of this study was to evaluate the available options for conducting remote activities such as inspection, testing, maintenance, and repairs on offshore wind turbines, both above and below the water line, by:

- Identifying commercially available technologies that can be used for remote monitoring, inspections, maintenance, testing, and repair
- Determining the types of inspections, testing, maintenance, and repairs that can be conducted remotely
- Developing a register of critical components that can be monitored inspected, tested, maintained, or repaired through RT
- Identifying current and future remote technologies
- Identifying best practices for documenting the results of remote activities (inspections, testing, maintenance, and repair).

This study, while comprehensive in breadth, represents a general survey of the state of RT rather than a deep dive into any given topic, and the intent of this report, along with the accompanying Excel workbook, is to serve as a useful reference for gaining insight into the current and developing capabilities of RT applied to offshore wind farm maintenance.

1.2 DNV's process/approach

To accomplish the scope outlined in Section 1.1, DNV took the following approach:

- Drew on internal experts in the areas of oil & gas, maritime, as well as both onshore and offshore wind to assess applicability of remote technologies for offshore wind farms
- Performed web-based searches for literature, publications, news articles, and marketing materials relevant to RT
- Conducted interviews, surveys, and internet research of a wide range of remote technology companies (see Appendix B for the full list) for the purpose of gathering the most current information regarding RT that is either already targeted to the offshore wind industry or has potential offshore wind applications.
- Developed a Register for each task where all task-specific information was logged and organized. The Register is an accompanying document to this report and serves as a reference tool.
- Applied DNV's standards, recommended practices, and guidelines related to remote inspection for offshore wind
- Selected a representative technology to "spotlight" for each Register that provides both a summary of that technology and why it was included in the report, and highlights where in the accompanying **Remote Technology Register** workbook to find further details. The intention of the Spotlights is to serve as an aid to navigating the workbook.

The study also assessed potential risks and benefits of using RT for maintaining offshore wind farms, including safety, economic, and environmental impacts. By reviewing DNV's extensive standards, recommended practices, and guidelines related to offshore wind that both reference and are used internationally, this study highlights how RT supports a risk-based inspection (RBI) framework for offshore wind farms.

2 PROJECT OVERVIEW

Offshore wind turbines today require condition-monitoring systems (CMS) to facilitate real-time tracking of overall system health and preventive maintenance campaigns. In addition, efforts are being made to conduct more and more maintenance activities using remote technologies, both to increase safety of personnel and to reduce maintenance and repair costs. The offshore wind industry is poised to take advantage of the experiences of the oil & gas, maritime, and onshore wind industriesby using remote technologies to conduct inspections, testing, maintenance, and repairs. This study presents a comprehensive overview of the state of RT as applied to maintenance activities in the offshore wind industry, and evaluation of the available options, including the risks and benefits of conducting remote inspections, monitoring, maintenance, testing, and repair of offshore wind turbines, both above and below the water line.

2.1 Project description

The study reviewed nine aspects related to the current and future application of remote technologies to maintaining offshore wind farms, as listed in Table 2-1, and findings are summarized in a series of Registers in the workbook **10311530-HOU-XL-01-B RemoteTechnology.xlsx ("Remote Technology Register")**.

Table 2-1 RT aspects explored in this study

Register #	Description
	Research, determine, document, and present…
1	different remote monitoring **methods** (e.g., visual, ultrasonic, thermographic, vibration, audible)
2	…the different types of commercially available **Remote Inspection Technologies** (RITs) (e.g., Unmanned Aerial Vehicles (UAVs), Remotely Operated Underwater Vehicles (ROVs), and Robotic Crawlers)
3	a list of **critical components** of an offshore wind turbine and electrical service platform that can be inspected, tested, calibrated and/or repaired remotely using commercially available technology
4	international offshore wind developer **remote inspection programs**
5	optimal **remote inspection intervals** in conjunction with staffed inspections
6	current U.S. and international **industry standards, practices, guidelines** that can be met by employing RITs above and below the water line
7	how remote systems could perform **maintenance, testing, repairs and component replacements**. This could be limited to replacing small parts, cleaning, lubrication etc.
8	the different types of **remote systems under development** and present what duties they are planned to conduct (inspections, testing, maintenance, repair, etc.), both above and below water line
9	best practices for **documenting the results** of the remote inspections, maintenance, testing, and repair

Offshore wind farms consist of wind turbine generators (WTGs) mounted on substructures that are embedded in or anchored to the seabed as well as the electrical infrastructure needed to bring the electricity to shore. Figure 2-1 shows the basic components of fixed-bottom WTGs, where the WTG consists of the rotor nacelle assembly (RNA) plus the tower, the substructure includes all equipment from the seabed to the bottom of the tower, and the foundation includes everything resting on or embedded in the sea floor. Several types of fixed-bottom substructures and foundations are shown, typically dictated by the seabed conditions and water depth. Figure 2-2 shows a similar schematic for floating foundation types, where the substructures consist of the floater plus mooring lines kept in place with anchor foundations. Several example floater and mooring line designs are shown. Figure 2-3 shows all the components of a wind farm, including electrical array cables running between turbines and the offshore substation (OSS), and then one or more export cables bring the electricity from the OSS to an onshore substation, then to the electrical grid. Together Figure 2-1 through Figure 2-3 show the range of components and subsystems that require proper maintenance over the lifetime of the wind farm, typically 30 years or more. This study explored the many ways RT is being used to accomplish that while reducing operation and maintenance (O&M) costs and increasing personnel safety.

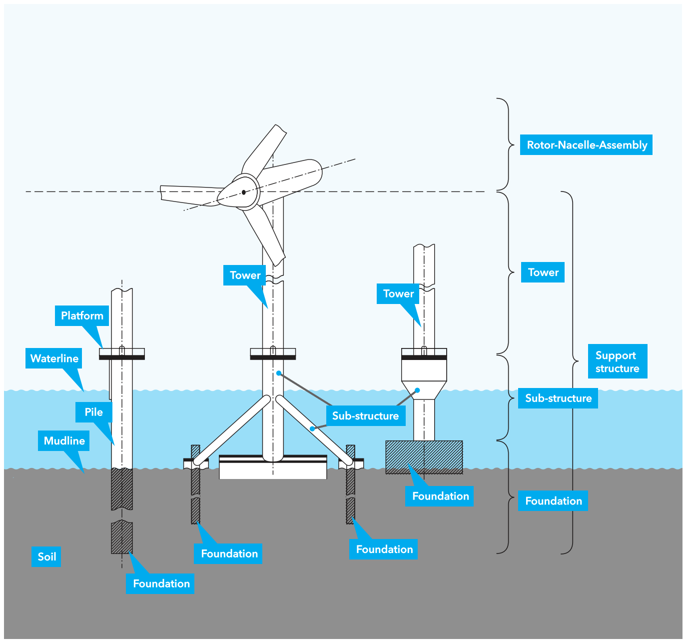

Figure 2-1 Components of fixed-bottom wind turbine systems [3]

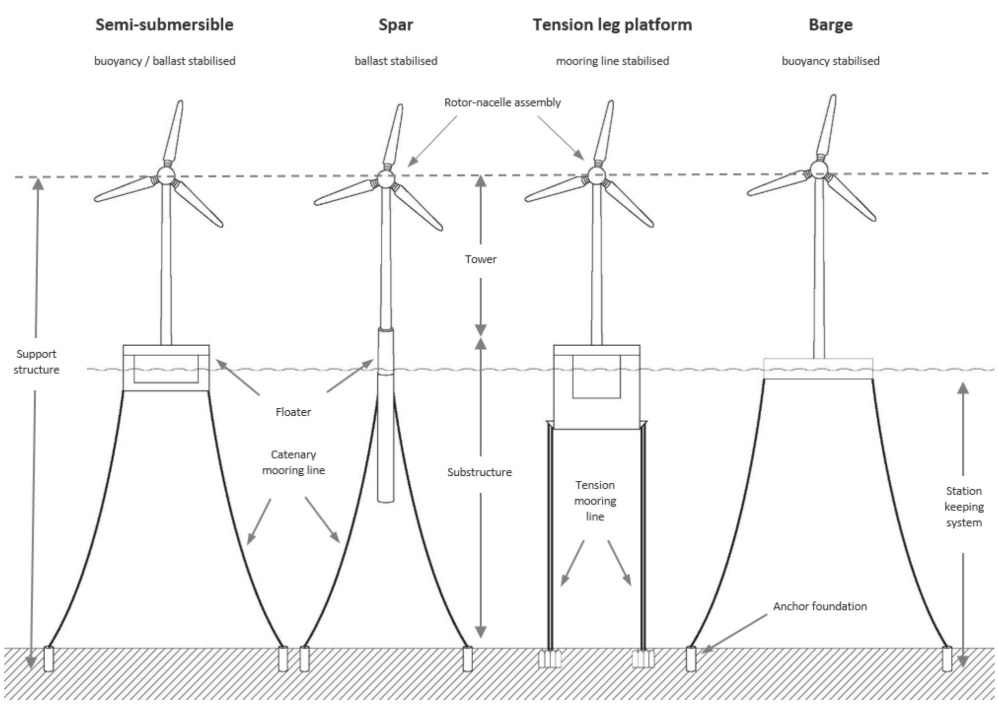

Figure 2-2 Components of floating wind turbine systems [4]

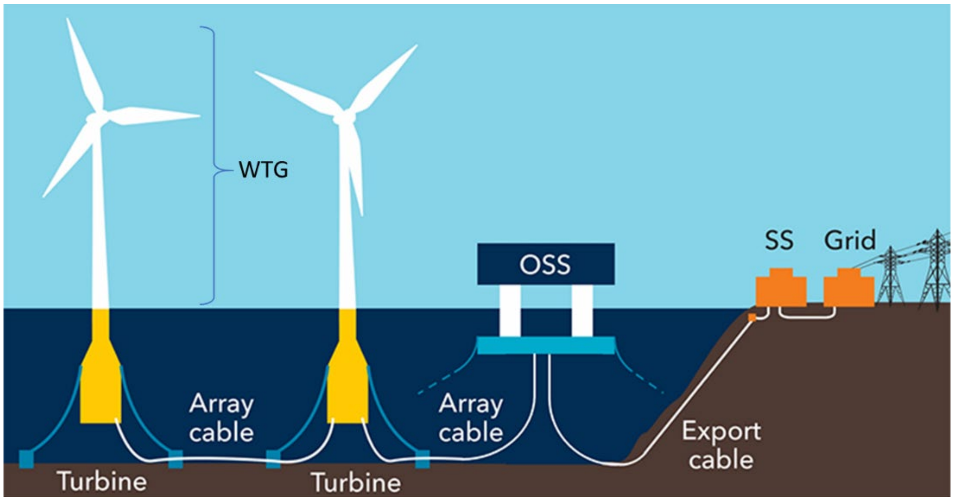

Figure 2-3 Components of a typical offshore wind farm (DVNV)

3 REMOTE TECHNOLOGY REGISTERS

3.1 Remote monitoring methods (Register 1)

Monitoring methods include diagnostic and prognostic activities that provide qualitative and quantitative feedback on the structural and functional status of the various critical components of a wind turbine, foundation, and offshore substation. In offshore environments, structures are subjected to severe atmospheric and oceanographic conditions and are, therefore, susceptible to numerous maintenance issues. Regular monitoring and inspections are essential to detect and prevent damage to critical components. Traditional methods of inspection, however, require personnel to overcome harsh offshore environments and to face risks to their health and safety. As a result, remote monitoring methods are increasingly being employed to improve personnel safety and reduce costs associated with extensive periods of operational downtime. DNV documented a list of remote monitoring methods currently in use in the accompanying **Remote Technology Register,** sheet ”**Register 1**”, and summarized below.

Remote monitoring employs methods and tools such as visual imaging, radiographic imaging, ultrasonic testing (UT), thermographic measurements, vibration measurements, acoustic measurements, strain measurements, magnetic flux measurements, and virtual simulations, among others. These methods use a variety of equipment, including cameras, sensors, fiber optic cables, and models to collect photos, videos, scans, signals, measurements, and time series data associated with relevant components. The data collected through these monitoring methods is processed and interpreted to diagnose and, potentially, prevent failures associated with several types of damage, including delamination, erosion, cracking, abrasion, corrosion, stretching, loosening, leaking, clogging, and overheating. These monitoring methods also present advantages and disadvantages related to technology availability, cost, accuracy, maturity, sensitivity to ambient conditions, and potential risk to personnel. The focus of **Register 1** is to detail the main remote monitoring methods being deployed in offshore wind farms and other offshore operations. Table 3-1 lists the methods investigated in this study, along with a brief description of each.

Table 3-1 Remote monitoring methods

Monitoring Method	Description
Visual Inspection	Visual inspection of external surface to identify surface condition.
Radiographic Inspection	X-rays allow inspection of internal components made of materials through which X-rays can travel.
Ultrasonic Inspection	Ultrasonic waves transmitted into materials to detect internal flaws or characterize external surfaces as well as internal areas in metallic and non-metallic (e.g., composite) components.
Thermographic Inspection	A nonintrusive, usually non-contact inspection technique that involves measuring temperature. Can be used to get a point measurement or provide a contour map showing temperature variations over an area.
Infrared Thermography	A specific type of thermographic inspection that measures temperature differences to within 0.05 ° C. Provides a contour map showing temperature variations over an area, where thermal signatures may be caused by friction in structural cracks, or changes in air flow such as boundary layer turbulence over a blade.
Accelerometer	Measures vibrations, detecting specific frequencies related to structures (e.g., natural frequencies) and rotational components (e.g., gear mesh frequencies)
Acoustic Emissions	Measures acoustic signals from an elastic wave (20-1000 kHz) generated by rapid release of energy from within a material. Can be cracking or popping noises due to structural damage, or tonal signals due to air passing over a feature (e.g., on blade surface)
Microwave	Detects changes in dielectric constant of materials
Fiber Optics	Measures strain
Fiber Optics - Optical	Time domain reflectometry is used to identify anomalies in the fiber optic cable (embedded in subsea cable) along its length
Fiber Optics - Thermal	Distributed Temperature Measurement System (DTMS) uses the change in optical signal to determine the temperature of the fiber optic and therefore adjacent conductor/cable
Strain Gauges	Measure state of strain [stress] of a structure using a gauge attached to the structure
Digital Twin	Virtual model (software tool) designed to accurately reflect a physical system. The tool collects and processes various inspection data to represent the state of the components and predict their behavior.
Magnetic Flux Leakage	Magnetic field applied to external post-tensioned tendons, metallic cables, steel structures to detect location and extent of corrosion
Coupon Inspection	Small samples of materials that are exposed to the environment in operating equipment. They are removed at specified intervals and inspected to monitor structural/material integrity.

For each monitoring method identified in Table 3-1, the **Register 1** provides the following details:

- Description of the monitoring method
- Type of equipment used to implement the monitoring method and indication of whether this equipment is embedded within or external to the system or component that is being monitored
- Type of equipment that may be monitored using the monitoring method
- Failure modes that can be identified using the monitoring method
- Advantages and disadvantages (technical and economic)
- Extent of current use in the wind industry
- Applicability in either above water line (AWL) and/or below water line (BWL) environments
- Format of the data likely to be gathered and methodology for data processing

The technologies used to employ these remote monitoring methods are further discussed in Section 3.2.

Spotlight on Ultrasonic Inspection

The **Register 1** sheet in the **Remote Technology Register** workbook includes additional details of the 15 methods listed in Table 3-1. One of those methods, Ultrasonic Testing (UT), detailed in Row 7 of **Register 1**, is spotlighted here as an example of the type and scope of information provided in the register for each monitoring method.

UT inspections use ultrasonic waves that are transmitted into materials to detect internal flaws or to characterize external surfaces and/or internal areas in metallic and non-metallic components. Different UT techniques include Pulse Echo UT, Phase Array UT, and Air Coupled UT. The Pulse Echo method transmits ultrasonic pulsed waves which are then reflected by the inspection area and obtained by the receiver to determine defects or discontinuities. The Phase Array method uses a beam from a phased array probe that can be focused and electronically swept across an inspection area without having to move the probe. Inspection with Air Coupled UT methods uses air as a medium to transmit ultrasonic energy, instead of water or gel.

UT inspection is typically carried out using a portable ultrasonic inspection probe, which can be used to inspect foundations, moorings, cable systems, blades, welds on tower, etc., to help identify insulation damage, structural damage, degradation, and aging. In the offshore wind industry, UT methods can be used to conduct AWL or BWL inspections of welds on towers, turbine base, substructures and foundations.

UT inspections store data through scans and measurements. Once a UT scan is complete, the data can be processed either though human inspection to identify defects and record measurements or through a machine learning tool that inspects scans to identify and log anomalies. Logged anomalies are then verified and catalogued by humans.

UT inspections can be more accurate than visual inspections due to the ability to measure thickness and to produce high quality scans of cracks and welds. UT is a well-established non-destructive inspection method.

UT inspection can be limited due to the cost of the equipment and the need for certified experts to post-process and accurately interpret that data. UT is not suitable for certain materials, odd shapes, small objects, or rough materials. Also deploying the equipment offshore can be challenging. Employing UT in offshore remote monitoring is a developing technique.

More information about other monitoring methods can be found in the **Register 1** sheet.

3.2 Remote inspection technologies (Register 2)

Remote inspection uses remotely operated and/or autonomous technologies to capture qualitative and quantitative data related to the condition of assets for off-site processing and analysis. These remotely operated technologies, commonly referred to as RIT, may be outfitted with a variety of payload devices and tools to perform inspection activities. Commercially available RITs include crawler robots, drones, ROVs, AUVs, and UUVs. A list of commercially-available RITs used in the offshore wind industry is detailed in the accompanying **Remote Technology Register** workbook, sheet “**Register 2**” and summarized below.

Above the water line, applicable RITs must have capabilities for mobility, automation, and precision to support inspection operations safely and efficiently. Crawlers, for instance, are equipped with wheels, tracks, or robotic legs and/or arms that facilitate autonomous navigation through complex and hazardous environments. Drones are aerial vehicles that provide stable and multi-directional maneuverability at a range of distances and heights. Both technologies can carry diverse payloads, including sensors and cameras, to support visual inspection, leak detection, and non-destructive testing with enhanced consistency, repeatability, and accuracy.

Below the water line, applicable RITs must exhibit stable swimming capabilities, structural robustness, and flexible configuration (e.g., modularity). Such technologies typically fall under the UUV family, which encompasses underwater vehicles that do not carry humans on board and are controlled remotely via cables, wireless communication, or pre-programmed commands. There are various types of UUVs, including ROVs and AUVs. An ROV is an unoccupied underwater robot that is tethered to a service vessel by cables, which transmit commands and data between the device and operator and provide power to the vehicle. An AUV is an untethered, autonomous vehicle that is either pre-programmed or remotely controlled by operators and stores collected data on onboard computers until the device is retrieved at the end of a dive. Typically, ROVs are used for missions involving manipulation of the environment, and AUVs are used for longer-term missions that do not require human intervention. AUVs rely on batteries for power and must be recharged regularly, sometimes at a charging station located at the seabed.

Register 2 presents a representative list of commercially available RITs currently in use to conduct inspections, including the different types of equipment (tools) installed. For each RIT, the register provides the following information:

- Equipment name, type, and manufacturer or service provider
- Number of years the technology has been used for commercial applications and, where applicable, project references
- Technical specifications, including maximum operating water depth, weight, and battery options
- Permanent or removable RIT tools that aid inspection
- Deployment method and location
- Offshore wind structures that may be inspected using the technology
- Capabilities for inspection, testing, and/or repair
- Level of autonomy, where 1 = human hand-operated, 2 = human-operated remotely, 3 = fully autonomous, i.e., no human intervention once deployed, and 4 = other
- Advantages compared to manual inspection
- Risks associated with the technology

The use of commercially available RITs for services other than inspection, such as maintenance, testing, and repair activities, is further discussed in Section 3.7.

Spotlight on Crawler Robots

The **Register 2** sheet in the **Remote Technology Register** workbook includes a list of 38 commercially available remote inspection technologies. One of these, the BladeBUG, detailed in Row 12 of **Register 2**, is spotlighted here as an example of the type and scope of information provided in the register for all the remote inspection technologies.

Crawler robots such as BladeBUG have the capability to inspect turbine rotor blades through visual and non-destructive testing inspection techniques.

The crawler robot has six independent legs that use suction to maintain connection to the blade surface as it remotely inspects the blade using a camera and ultrasonic sensor.

Initially made available three years ago, the robot is in the early commercial stage for onshore wind turbines. The BladeBUG crawler robot is semi-autonomous and can be operated out of line of site. It is deployed from the nacelle and eliminates the need for a technician to rappel down the blade, reducing risk to personnel as well as saving time. In addition, the BladeBUG can operate in higher wind speeds than is safe for a human, increasing the overall weather window for blade inspection. However, this technology does still require a technician to transfer from a vessel to the WTG platform and climb up the turbine tower to deploy the robot from the nacelle.

Residual risks of this technology for offshore wind deployment include 1) the need to transfer both crawler robot and technician to the tower platform and uptower to the nacelle, and 2) the risk of the robot falling from the blade (or tower) if the suction mechanisms fail. With six independent suction-feet, the likelihood of this latter failure mode is quite low.

Similar detail on the capabilities, advantages and risks of each of the other RITs studied is provided in **Register 2**.

3.3 Critical components for inspection using RT (Register 3)

The major elements of an offshore wind farm include wind turbines, foundations, and offshore electrical infrastructure including cabling, and offshore substations (See Figure 2-1 through Figure 2-3). Most of the more than 8,000 subcomponents comprising an offshore WTG are not subject to remote inspection. DNV identified the critical components (summarized below) of an offshore WTG and OSS that can be inspected, tested, calibrated, and/or repaired remotely using commercially available technology. Remote monitoring methods (Section 3.1) and remote inspection technologies (Section 3.2) summarize means for monitoring and inspecting these components critical to their structural and functional integrity and able to be accessed remotely. **Register 3** in the accompanying **Remote Technologies Register** workbook identifies these critical components. **Register 3 (a)** also includes a matrix of major failure modes, while **Register 3 (b)** identifies the remote monitoring method(s) associated with each component. Both are summarized below.

Above the water line, the major systems inspectable using RT include some components of the RNA, the tower, tower platform and the transition piece, as well as the OSS) and the portion of the OSS foundation that is AWL. The RNA is comprised of the rotor blades, rotor hub, generator, gearbox (if present), yaw system, control and power electronics systems, among other equipment, all contained within the nacelle housing. Rotor blades, attached to the hub, consist of an outer “skin” giving shape to the blade plus internal spars providing strength and stiffness. The skin is made of multiple layers of primarily glass fiber stiffened with balsa wood or other matrix material and infused with a heat-cured plastic resin. The skin has more layers (thickness) near the blade root than at the tip, based on the loading profile. The upper and lower skins are joined together and stiffened by one or more internal spars, typically made of a carbon fiber reinforced polymer (CFRP) to minimize weight. The outermost blade surface is protected by gelcoat or paint to resist erosion, especially along the leading edge. The blades must be submitted to regular inspections to detect erosion, cracking, and delamination, among other types of damage and are among the primary components for remote inspection.

The RNA sits on top of a tower made of either steel, concrete, or a hybrid of both materials. The tower is mounted either directly on the foundation or on a transition piece that connects the tower to the foundation. The tower plus the AWL part of the foundation/transition piece must be examined for corrosion as well as cracks resulting from fatigue loading or extreme loading. The OSS platform, including transformers, cranes, low-voltage (LV) electrical cabinets, piping, valves, emergency generators and boat landings can also be inspected similar to the WTG. Currently, backup gensets (combination of diesel engine and electric generator) for OSS Platforms use diesel fuel. They require proper maintenance, per the manufacturer's recommendations, including monthly testing, otherwise they can be hard to start remotely. The monthly testing can be done remotely by a technician from the onshore control room supervisory control and data acquisition (SCADA) system, or from another location. For example, the genset of the Arkona substation in Germany can be started via laptop from anywhere with internet access. The backup generators have a standby battery (truck battery) to restart independently. Charge level of the standby battery is also monitored via the SCADA system.

Drones and crawlers capable of conducting visual inspections, ultrasonic testing, thermography, and frequency monitoring facilitate the inspection of AWL components, most notably the rotor blades, tower, and OSS platform but also others as listed in **Register 3 (b).** A description of the specific RIT activity associated with each identified component is provided in Section 3.1.

Below the water line, major systems of an offshore wind farm include the turbine foundations (whether fixed-bottom or floating), mooring systems (if floating), and electrical cable systems. Both fixed-bottom and floating foundations are susceptible to corrosion, structural damage, and external degradation. These systems may be assessed using visual imaging, ultrasonic testing, and coupon inspection methods. Electrical cables can also be evaluated for external corrosion and structural damage, and these systems may also be inspected to assess normal operations, insulation damage, bending, and surfacing from recommended burial depths. These cable systems may be examined using thermography, fiber optics, coupon inspection, visual imaging and electrical conductivity. UUVs, which can either be (AUV that operate free from human intervention or ROVs piloted remotely via an umbilical connected to a nearby vessel, support the inspection of such systems BWL and at the surface (see Section 3.2).

BWL OSS components that can be inspected remotely were also identified, including the overall exterior foundation structure (corrosion, build-up of sea-life) as well as interior (corrosion), high voltage (HV) cables and connectors, and scour protection.

Register 3 outlines offshore wind systems and their critical components and assesses them based on their safety and operational criticality, potential failure modes, and applicable methods for inspection. Standard failure modes include delamination, erosion, cracking, abrasion, corrosion, stretching, loosening, leaking, clogging, overheating, and other types of damage. Criticality is rated based on the type and severity of damage, such as cosmetic (no impact on operation, minor), functional (potential disruption to operation), major (asset failure), and structural (asset loss, catastrophic). Relevant methods for inspection are evaluated based on existing and potential practices. For each critical component, **Register 3** provides the following information:

- Name of critical system and associated components
- Criticality rating, where 1 = cosmetic, 2 = functional, 3 = major, and 4 = structural
- Part (a): a matrix of primary failure modes

- Part (b): methods of remote monitoring or inspection

Table 3-2 lists of critical systems and components that can be remotely inspected, as listed in the accompanying **Remote Technology Register** workbook, **Register 3 (a)** and **(b)**.

Table 3-2 Critical Components

	System	Critical Components
	Above Water Line	
Rotor Nacelle Assembly	Rotor Blades	Skin (external)
		Skin (internal)
		Spar
		Bolts (blade root)
	Rotor Hub	Cast Iron Body
	Main Bearing	Races and Rollers
		Cast Iron Housing
	Mainshaft/Kingpin	Forged Or Cast Body
	Generator	Direct-Drive Windings and Magnets
		Direct-Drive Rotor and Stator Housings Carry High Torque Loads
		Medium-Speed Windings and Magnets
		Bearings
	Gearbox (not relevant for direct-drive WTGs)	Gears
		Bearings
	Generator Frame	Main Weldment or Casting
	Bedplate	Cast Iron Body
	Yaw Drive	Yaw Motors Gearboxes, Pinion, Bearings, Slewrings
	Power Electronics	Electrical Components
Tower		Steel
		Concrete
		Hybrid (Steel + Concrete)
		Bolts
Offshore Substation (OSS) Platform		External Coating
		Internal Coating
		Above Water Structure
		Boat Landing
		Cranes
		Transformer
		HV geographical information system (GIS)
		HV Cables and Connectors
		LV Electrical Cabinets
		Piping
		Valves
		Emergency Generators
		Rotating Equipment
	Below Water Line	
Foundations		Concrete/grativy-based foundation (GBF)

	Steel Structure (Monopile, Transition, Piece, Jacket)
	Bolting
	Scour Protection Material
Floating Hull	Concrete Based Structure
	Steel Structure
Corrosion Protection (CP) System	Anodes
Mooring	Polyester
	Ultra-High Molecular-Weight Polyethylene
	Chain
	Anchor Piles
Electrical Cable System	Hangoff Assembly
	End Connection
	Bend Stiffener/Restrictor
	Subsea Cable Array
	Subsea Cable Export
	Ancillary Strakes, Clamps, Buoys
	Cable Protection System on Seabed
OSS Substructure	Jacket Structure
	Anodes
	ICCP Electrodes
	HJ-Tubes
	Scour Protection
	Boat Landing

The **Register 3** sheet in the **Remote Technology Register** workbook includes the critical components listed in Table 3-3. Rotor blade components, detailed in Rows 7-10 of **Register 3**, are spotlighted here as an example of the type and scope of information provided for AWL critical components. Foundation components, detailed in Rows 43-46 of **Register 3**, are spotlighted here as an example of the type and scope of information provided for BWL critical components.

Spotlight on Rotor Blade Components (AWL)

The rotor blade system is located entirely above the water line and has several critical components that require inspection that can be done remotely. The skin of the rotor blade includes all layers of the composite laminate, the thickness of which decreases from blade root (thickest) to tip (thinnest) based on the blade loading profile. The external skin component may experience leading edge erosion, skin cracking, lightning damage, and delamination. Issues with the external skin can lead to functional failure. The internal skin of the rotor blade can experience cracking or delamination. Depending on the severity, issues with the internal skin can lead to functional or major failure. The spar component can experience cracking or lightning damage, which can lead to major damage. The bolt, or blade root, component can experience stretching (loosening), fatigue cracks, or shear, which can lead to major failure.

Register 3 (b), rows 7-10, identifies specific remote monitoring/inspection technologies for each rotor blade component: skin, spar, and blade root bolts. For example, all can be visually inspected using either a drone or a crawler fitted with a high-definition () camera. The use of ultrasonic inspection is also identified. Other technologies, such as acoustic emissions or fiber optics are noted as not technically ready or under development for this application. The use of a Digital Twin (DT) is identified as a potentially good way to monitor leading edge erosion, a key cause of performance degradation requiring regular blade maintenance.

Spotlight on Foundation Components (BWL)

The turbine foundation is made up of several below water line components. As detailed in **Register 3 (a)** rows 43-46, the steel structure of the foundation (monopile, transition piece, or jacket) can experience corrosion, structural damage, grout failure (in its transition piece), buckling, pile pull-out, and shear failure. Damage to the steel structure of the foundation can result in catastrophic failure. Bolted foundation components can experience corrosion, stretching (loosening), fatigue, and shear failure that if undetected can result in major failure. The scour protection material component can experience shifting due to currents, which can also result in major failure if not addressed. The concrete GBF can experience erosion due to chemical interactions with sea water, corrosion of steel elements such as rebar, and physical abrasion. Damage to the concrete based component can result in catastrophic failure.

Register 3 (b) highlights the types of remote inspection or monitoring available for foundations. Visual inspection via ROV or AUV mounted with HD video and still cameras is the primary (RT)currently available to detect structural damage, external degradation, external corrosion, or cracking. Digital Twins can also be used to monitor fatigue life of foundations. In addition, coupon testing is often used to assess corrosion, but the coupons themselves must be retrieved in order to be evaluated. It’s possible for this to be accomplished using an ROV/AUV with a robotic arm.

Summaries of the other components listed in Table 3-3 can be found in **Registers 3**.

3.4 Remote inspection programs (Register 4)

The demand for increased safety in the maintenance&M of offshore wind farms is a major driver for innovation in technologies and procedures related to remote inspection. Wind farm operators, for instance, benefit from a wide range of RITs that are increasingly in mainstream use or that are being adopted in the offshore wind industry. As experience with the operation of offshore wind farms grows globally, operators also benefit from the successes and lessons learned from existing projects at various stages of operation. While international experience is invaluable in this rapidly growing industry, operators must also frame such global learnings within the context of the appropriate regulatory landscape. In the U. S., the Bureau of Ocean Energy Management (BOEM) has established procedures and obligations for renewable energy activities on the Outer Continental Shelf (OCS) through the Code of Federal Regulations (CFR), specifically Title 30 – Part 585 "Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf" (30 CFR 585). Therefore, offshore procedures, including those relevant to inspection operations, must be compliant with 30 CFR 585 regulations [5].

Regulations for inspections are detailed in 30 CFR 585 – Subpart H "Environmental and Safety Management, Inspections, and Facilities Assessments for Activities Conducted Under SAPs, COPs, and GAPs". These regulations state that BSEE will conduct both scheduled and unscheduled inspections of OCS facilities and that the operator must also develop a comprehensive annual self-inspection plan for these facilities (Figure 3-1). The annual self-inspection plan must describe the type, extent, and frequency of inspections for AWL and BWL structures and the methods for monitoring the corrosion protection of these structures. These regulations also state that an annual report must be submitted to BOEM with a list of facilities inspected in the preceding 12 months, the inspection methods employed, and a summary of the overall condition of the facilities, including any repairs performed.

RITs can support the implementation of annual or, in certain cases, semi-annual inspections, as well as non-scheduled inspections, for example after an extreme weather event or an impact, as required by 30 CFR 585. For instance, AWL annual inspections of the turbine blades may be conducted with visual imaging of the blade exterior using drones and ultrasonic inspection of the blade interior using crawlers. Annual inspections of other AWL external structures, such as the tower, nacelle, and foundation platform, may also be conducted with using drones fitted with HD cameras. BWL annual inspections of foundations are conducted with UUVs (either AUVs or ROVs) for the exteriors and with a combination of UUVs and divers for the interiors. Additionally, UUVs are also increasingly being used to conduct annual inspections of subsea cables and semi-annual inspections of mooring lines.

Offshore wind projects have benefited from the increasing adoption of RTs through cost and time savings and increased safety. With RITs, inspections may be performed on multiple structures on a given day in a wider range of weather or marine conditions, thereby reducing schedule risk and associated costs as well as averting safety risks to personnel. Still, RTs experience certain limitations and may pose challenges compared to manned procedures. For instance, AWL drones may pose a higher risk of accidental damage to structures and are comparatively less nimble than human counterparts for unplanned operations. Additionally, BWL UUVs may experience limitations associated with environmental conditions and have reduced capabilities for the inspection of interiors.

Register 4 in the accompanying **Remote Technologies Register** workbook explores the types of remote inspection programs currently found in the offshore wind industry. **Register 4** adds context to the current understanding of remote inspection methodologies (Section 3.1), RITs (Section 3.2), and the offshore wind systems that may be serviced by such technologies (Section 3.3) by considering current practices, including industry successes and failures. **Register 4** also frames these practices and their associated learnings within the context of the regulations set in 30 CFR 585 for self-inspection. The register presents a list of remote inspection practices. For each practice, the register provides the following information:

- Inspection type and indication if inspection is remote or manned
- Components that may be inspected using the identified inspection method and/or technology
- Purpose and/or description of the inspection
- Potential failure modes of the identified components

- Lessons learned, including successes (advantages) and failures (disadvantages), of the identified inspection method and/or technology
- Description of how remote inspections support and/or enhance complains with compliance with 30 CFR 585, Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf. Information to be included in comprehensive annual self-inspection plans of above-water and below-water structures:
  - Frequency and extent of in-situ inspection.
  - Description of corrosion protection monitoring.
  - Facilities inspected in the preceding 12 months.
  - Types of inspections, including remote methods.
- Extent of application of program in the offshore wind industry

§ 585.824 How must I conduct self-inspections?

(a) You must develop a comprehensive annual self-inspection plan covering all of your facilities. You must keep this plan wherever you keep your records and make it available to BOEM inspectors upon request. Your plan must specify:

(1) The type, extent, and frequency of in-place inspections that you will conduct for both the above-water and the below-water structures of all facilities and pertinent components of the mooring systems for any floating facilities; and

(2) How you are monitoring the corrosion protection for both the above-water and below-water structures.

(b) You must submit a report annually to us no later than November 1 that must include:

(1) A list of facilities inspected in the preceding 12 months;

(2) The type of inspection employed, (*i.e.*, visual, magnetic particle, ultrasonic testing); and

(3) A summary of the inspection indicating what repairs, if any, were needed and the overall structural condition of the facility.

Figure 3-1 Description of self-inspections, per 30 CFR 585.824

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Spotlight on Inspection Regulations for Rotor Blade Components

The **Register 4** sheet in the **Remote Technology Register** workbook includes the inspection programs that support compliance with 30 CFR 585 regulations for offshore activities. The inspection programs for rotor blade components detailed in Row 2 and Row 3 of **Register 4**, respectively, are spotlighted here as examples of the type and scope of information provided in the register.

The regulations established in 30 CFR 585 for offshore renewable energy activities require wind farm operators to develop an annual self-inspection plan for AWL and BWL structures. The self-inspection plan must describe the type and timing of inspections of offshore structures and the methods for monitoring the corrosion protection of these structures. Rotor blades must be inspected for various forms of damage and degradation to both exterior and interior components. Drones and crawler robots can perform visual, thermographic, and UT inspections of the blade exteriors and interiors; the use of these technologies and methods can be described in the annual self-inspection plan. Inspections of the blade exteriors and interiors are typically conducted on an annual basis, and the findings of these inspections must be reported annually to comply with 30 CFR 585 regulations. The inspection of rotor blade exteriors should include an assessment of anti-corrosion coatings using thermographic inspection methods to check for surface degradation and corrosion from ultraviolet radiation. The inspection of rotor blade interiors should first include a baseline corrosion protection survey to confirm fitness for service and continued protection from the cathodic protection system to prevent integrity issues.

The critical components associated with rotor blades and the types of damage for which these components should be inspected are detailed in Section 3.3's **Spotlight on Rotor Blade Components (AWL)**. The inspection intervals recommended for rotor blades, as recommended or required by industry standards, are detailed in **Spotlight on Inspection Intervals for Rotor Blade Components**, Section 3.5.

3.5 Remote Inspection Intervals (Register 5)

The rapid growth of the offshore wind energy sector and increased adoption of innovative technologies for offshore operations has highlighted the need for a deeper understanding of inspection demands and requirements for offshore systems. Beyond the inspection requirements set by BOEM in 30 CFR 585 (Section 3.4), recommendations for particular systems have also been outlined in established industry documents, including standards, recommended practices, service specifications, and offshore standards. Such documents, for instance those developed and maintained by DNV, provide principles, requirements, and guidance for the responsible and safe operation of wind farm systems and are summarized in Section 3.6.

Industry standards generally reference two approaches to inspecting and maintaining systems – a prescriptive approach and a risk-based inspection (RBI) approach. A prescriptive approach is based on requirements established by standards based on previous experience and safety studies. A risk-based/condition-based approach uses nondestructive technology to monitor or inspect asset health and provides critical input to the maintenance program. Standards may suggest either approach or a combination of both for certain systems.

The objective of **Register 5** in the accompanying **Remote Technologies Register** workbook is to identify what an "optimal" remote inspection interval might be for each critical component defined in Register 3 (Section 3.3), in conjunction with manned inspections. In other words, there is always an interface between what the RT can accomplish and the residual task or tasks that still need to be carried out by technicians. The approach and timing of inspections are largely dependent on the components being inspected and their location. The frequency with which inspections are conducted may be set with consideration for the structural and functional criticality of a particular system, evolving condition of the facility across the project lifetime, potential consequences of structural failures on the surrounding environment, and changing conditions at the site. Ultimately, however, inspection frequencies must adhere to recommendations set by the original equipment manufacturers (OEMs), wherever applicable, or be based on condition monitoring. Furthermore, they must comply with established standards and regulations.

For AWL, turbine blades are to be assessed at an inspection frequency specified by the OEM, typically annually unless condition-based monitoring is employed. Blade and tower exteriors may be inspected remotely using a drone operated from a nearby vessel, eliminating the need for a technician to transfer to the WTG platform, climb the tower, and rappel down the blade or tower exterior. This approach saves time and money and improves safety of that inspection activity. Remote inspection of the blade *interior* still requires personnel operating drones or crawlers to transfer from a vessel to the turbine platform, climb the tower, and enter the hub, where the drone or crawler is then deployed. While inspecting the blade interior carries greater risk than inspecting the exterior, employing a drone or crawler does still eliminate the need for personnel to work inside the blade, thus eliminating one time-consuming and risky task. Similar to the rotor blades, turbine tower exteriors can generally be inspected by drones operated from a nearby vessel. The recommended inspection interval for both steel and concrete towers is generally annual but steel towers may require special consideration depending on the safety factor (SF) of the design.

For BWL and in the highly corrosive splash zone (i.e., the section of the structure that is intermittently in or out of seawater due to changes in tidal and wave conditions), turbine foundations are generally treated with condition-based inspections and require the use of multiple inspection technologies for the various structures and surfaces. For instance, drones are well suited for visual inspections of coatings, chains or ropes, and other structures above and/or in the splash zone, while ROVs are capable of monitoring and in some cases restoring coatings on, cables, anchors, and other structures BWL.

Register 5 assesses the approach and timing of inspections for the various critical components of an offshore wind farm, with particular attention to guidelines and recommendations set in industry standards, recommended practices, and service specifications. A register of inspection practices and intervals for critical components was developed. For each critical component, the register provides the following information:

- Name of critical system and associated components
- Recommended inspection interval based on industry standards and guidelines
- Description of RIT inspection activities
- Description of manned inspection activities
- Document number of the industry standards and guidelines establishing the referenced inspection requirements Each document number is linked to a description of the document in **Register 6**

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Spotlight on Inspection Intervals for Rotor Blade Components

The **Register 5** sheet in the **Remote Technology Register** workbook includes the recommended intervals and joint RIT and manned activities for the inspection of critical components. The inspection intervals and activities for rotor blade components, detailed in Rows 1-4 of **Register 5**, are spotlighted here as an example of the type and scope of information provided in the register for each critical component.

The critical components of the rotor blade system are the external skin, internal skin, spar component, and blade root bolts. The remote inspection intervals for these components suggested by the associated OEMs are typically annual. Recommended inspection intervals for rotor blade components are specified in “Rotor blades for wind turbines” (DNV-ST-0376) and “Machinery for wind turbines” (DNV-ST-0361).

The blade exterior can be inspected using drones, and the blade interior can be inspected using either drones or crawler robots. Inspection of the external skin involves directing a drone to fly in a pattern along the blade length to capture videos and high-resolution still photos of areas of interest, inspect the structural integrity of laminates, and assess the condition of adhesive joints at the leading and training edges of the external skin. Inspection of the internal skin, spar, and blade root involves a similar process of directing either a drone or a crawler robot along the blade length to capture videos or photos of areas of interest, inspect the structural integrity of laminates, assess the adhesive joints and attached items on the internal skin, and assess bolt markings of the blade root to check for any signs of loosening.

In conjunction with the operations performed by remote technologies, inspections also require on-site personnel to perform a series of tasks. The inspection of the blade exterior requires personnel to deploy and operate drones from vessels located near the turbine, an approach which eliminates the need for technicians to climb up the tower and rappel down the length of the blade. The inspection of the blade interior, specifically the internal skin and spar, requires operators to direct the drone or crawler robot from the rotor hub or blade root. In this situation, the operator transfers from the nearby vessel to the turbine, climbs the tower to the nacelle, and enters the hub. Still, using a drone or crawler robot to inspect the blade interior eliminates the need for an inspector to enter and walk/crawl through the confined space of the blade. Additionally, the inspection of the blade root also requires an on-site inspector to manually spot-check bolt pre-tension, in particular for areas of interest captured by the drone or crawler robot.

Refer to **Register 5** of the workbook for details of remote inspection intervals for other critical components.

3.6 Industry standards, recommended practices, and guidelines that can be met by RT (Register 6)

Recommendations and requirements for wind farm inspections are established in industry standards, service specifications, and offshore standards, which provide principles, requirements, and guidance for inspecting offshore wind farm components and systems with the goal of ensuring an acceptable level of safety and reliability of relevant structures and, in some cases, to serve as a basis for verification of these structures.

In **Register 6** of the accompanying **Remote Technologies Register** workbook, DNV standards, practices, and guidelines applicable to offshore wind components and subsystems were reviewed and sections related to inspection summarized. RITs capable of meeting each standard were identified and logged in the register. Note that the referenced DNV standards may be accessed from DNV rules and standards.

DNV has developed and maintains a series of standards and guidelines related to both physical and digital systems relevant to the operation of offshore wind power plants. The physical systems for which DNV has established requirements and recommendations include wind turbine towers, rotor blades, condition monitoring systems (CMS), other wind turbine machinery (e.g., gears, bearings, brakes, couplings, corrosion protection, and bolted connections), foundations (e.g., monopile, jacket, tripod, suction bucket, and floating structures), mooring systems for floating foundations, subsea power cables, and offshore substations. In addition, the digital systems for which DNV has established standards and recommendations includes data quality assessments, data management, cyber security, and the use of digital twins. DNVs standards and guidelines reference a wide array of international standards and are themselves in wide use internationally, providing a comprehensive set of standards against which to evaluate the ability of RITs to meet them.

As described in Section 3.5, wind farm assets may require periodic (i.e., prescriptive) inspections and/or condition-based inspections, which may also include inspections necessitated by environmental events (e.g., icing, extreme temperatures, and seismic events). For the physical assets of a wind farm, the appropriate inspection requirements and recommendations may be increasingly addressed with RITs that may also be employed in conjunction with continuous monitoring from CMS, which measure parameters such as vibrations, structure-borne sounds, temperatures and/or loads to determine the overall health of the monitored components.

Periodic inspection and monitoring during the in-service phase of a project (i.e., after the start of operation) is required to maintain project certificate(s). The service specifications published by DNV, “Project certification of wind power plants” (DNV-SE-0190), outline the assets that are to be inspected (e.g., wind turbines, substations, and power cables) and the types of damage that should be the focus of these inspections (e.g., fatigue cracks, deformations, corrosion, scour, marine growth, bolt pretension). These in-service inspection activities are required on a regular basis. Operators must ensure that all assets are inspected at least once during a five-year period, with more frequent inspections conducted during the first five-year period of operation. Remote inspection technologies (e.g., drones and crawlers) are considered to be appropriate alternatives to on-site or in-person visual methods and can be used in conjunction with real-time data from the CMS.

Support structures for wind turbines, including floating foundations generally follow condition-based plans for in-service inspections. The standards published by DNV with requirements for in-service inspections include “Support structures for wind turbines” (DNV-ST-0126), “Floating wind turbine structures” (DNV-ST-0119), and “Floating offshore wind turbine installations” (DNV-RU-OU-0512). These standards specify that adequate inspection and maintenance is to be performed based on a systematic assessment of potential failures from CMS data, though the frequency of inspection of critical items should not exceed one year. Inspections should follow a program specifically developed for the design of structures and the environmental conditions at the site. Underwater components of support structures may be examined using UUVs, (ROVs and AUVs), equipped with cameras, sensors, and scanning tools.

Special environmental scenarios should also be considered for remote inspection and monitoring, including icing, extreme temperatures, and seismic events. The recommended practices outlined in “Icing of wind turbines” (DNV-RP-0175), “Extreme temperature conditions for wind turbines” (DNV-RP-0363), and “Seismic design of wind power plants” (DNV-RP-0585) address the management of a range of components under these conditions. For instance, ice detection should be incorporated into the monitoring and inspection of blades, hub, nacelle, and tower of wind turbines exposed to icing conditions. Wind turbines in extreme temperature conditions should be inspected for potential damage or failures of the heating/cooling systems, control systems, and insulating materials. Additionally, the various assets of a wind farm should be immediately assessed following a significant earthquake event, and special attention must be given to turbine blades and machinery components. Drones are well-suited to conduct inspections following extreme events.

Register 6 provides a detailed assessment of the requirements and recommendations outlined in industry standards, recommended practices, service specifications, guidelines, and offshore standards with emphasis on the RTs that can be used to fulfill these requirements. For each industry document, the register provides the following information:

- Document number and title of industry standard, recommended practice, or guideline
- Sections within the document that provides information relevant to inspection
- Summary of the requirements and recommendations regarding inspections outlined in each document
- Applicable RIT activities including how they meet the standard, guideline, or practice

Spotlight on Industry Standards for Floating Turbine Structures

The **Register 6** sheet in the **Remote Technology Register** workbook summarizes DNV's industry standards, recommended practices, service specifications, offshore standards for offshore wind, data management and cyber security. One of these standards, "Floating wind turbine structures" (DNV-ST-0119), detailed in Row 11 of **Register 6**, is spotlighted here as an example of the type and scope of information provided in the register for the industry documents considered in this assessment.

DNV-ST-0119 is an industry standard that provides principles, technical requirements, and guidance for design, construction, and in-service inspection of floating wind turbine structures. This standard recommends inspection and maintenance to be performed based on potential failures. The purpose of inspection is to detect defects that may grow into more severe degradation or cracks during the service life of the structure. Components are assessed based on the potential consequences of failure and the stress condition which may provoke fracture. Components susceptible to degradation should be submitted to general visual inspections at least every 4-5 years. Inspection of corroded steel structures should include measurements of plate thicknesses obtained using UT methods. Additionally, special provisions for critical components requiring inspection and repair during service life are planned as early as the design stage. For instance, DNV-ST-0119 highlights the importance of proper planning in positioning critical welds in locations on the inside of the hull for greater access for inspection and repair.

Additionally, DNV-ST-0119 references "Position mooring" (DNV-OS-E301) for inspection guidelines for anchors, mooring chains, and steel tendons. DNV-OS-E301 specifies the minimum corrosion allowance for chain and connection elements based on the frequency of inspections performed on the various segments of a mooring line. DNV-ST-0119 also references (DNV-OS-E303) for inspection guidelines for fibre ropes, tethers, and tendons. DNV-OS-E303 specifies that an inspection and test plan must be issued by the rope manufacturer. The in-service condition management program must be based on tension monitoring and control of temperature.

RIT technologies with capabilities to support inspection activities as specified in DNV-ST-0119 for floating turbine structures include drones, crawlers, ROVs, and AUVs. Drones outfitted with cameras and crawlers with capabilities for UT testing and magnetic flux leakage detection can be used to detect deformations, fatigue cracks, and steel thicknesses indicative of corrosion. ROVs and AUVs equipped with cameras and manipulator arms can support inspection and maintenance operations for underwater structures, including the mooring line system and ropes.

Refer to **Register 6** of the workbook for details related to other industry standards, guidelines, etc.

3.7 Commercially available RT for maintenance, testing, repairs and replacements (Register 7)

Remotely operated devices are increasingly being adopted for a variety of operations in addition to visual inspection. These devices include crawler robots, drones, and UUVs (including ROVs and AUVs), which can be equipped with a variety of payload sensors and tools to support not only inspection but also monitoring, testing, cleaning, repair and in some cases replacement of critical systems and components in an offshore wind farm. The application of these devices can also support compliance with the regulations and industry standards that ensure the safety and reliability of such structures (Sections 3.4-3.6). DNV documented commercially available RTs with multiple capabilities in the accompanying **Remote Technologies Register** workbook**,** sheet "**Register 7"**', and summarized below.

Recent technological advancements in modular designs have allowed remotely operated devices to carry more diverse payloads. These devices can be outfitted with sensors and tools used for testing, including (UT), Eddy current array testing (ECA), alternating current field measurement (ACFM), and hermal infared (IR) cameras. Additionally, these devices can accommodate tools for maintenance and repairs, including manipulator arms, grippers, torque tools, brush tools, compact cutters, water jet systems, tracking systems, high-intensity lights, high-definition cameras, and other attachments for cleaning and repairs.

Register 7 summarizes the capabilities of remotely operated systems to conduct maintenance, testing, and repair operations, with emphasis on technologies that are already commercially available. While many of these remote technologies were only recently launched into the market, a few devices have been commercially available since the early 2000s. Technologies with longer tenures in field work have historically been used for environmental monitoring, hydrography, recreation, search and recovery, military applications, and oil and gas industry operations. In recent years, however, these technologies have transitioned into the renewable energy industry, and their most recent designs reflect this increased adoption to new applications.

A register of commercially available technologies for remotely operated or autonomous maintenance, testing, and repair operations is provided in **Register 7** and includes the following information:

- Name of manufacturer, service provider, or operator of equipment
- Name and type of equipment
- Number of years the technology has been used for commercial applications and project references, where applicable
- Technical specifications, including equipment dimensions, weight, operating heights (above water) or depths (below water)
- Payload tools that support maintenance, testing, repairs, and inspection activities
- Deployment method and location
- Components that may be managed using the equipment
- Details regarding equipment capabilities for maintenance, testing, and repairs
- Level of autonomy, where 1 = human hand-operated, 2 = human-operated remotely, 3 = fully autonomous, i.e., no human intervention once deployed, and 4 = other
- Level of use for activities related to the wind turbines, both onshore and offshore
- Associated risks and benefits

Descriptions of RIT equipment (commercially available) for maintenance, testing, repairs, and replacements are presented in the accompanying **Remote Technology Register** workbook.

> **Spotlight on ROVs for Underwater Maintenance, Testing, and Repairs**
>
> The **Register 7** sheet in the **Remote Technology Register** workbook includes the commercially available remote technologies that support maintenance, testing, and repair operations. The Seaeye Cougar-XTi, an ROV, is detailed in Row 21 of **Register 7** and is spotlighted here as example of the type and scope of information provided in the register.
>
> Cougar-XTi, developed by Saab Seaeye, is a compact electric ROV with the ability to perform a range of underwater applications. The technical specifications of the ROV include dimensions of 1.5 m x 1 m x 0.8 m (length x width x height), operational depth of 2000 m, and launch weight of 435 kg. The ROV can be equipped with a large payload to accommodate quick-change tooling skids for inspection, maintenance, testing, and repair operations. Payload tools and accessories include high-definition (HD) cameras, a manipulator arm system, a compact cutter for steel wire ropes, rotary cutter for hoses and cables, heavy duty cleaning brush, water jet system for cleaning operations, and UT system. The ROV, equipped with the aforementioned tools, services underwater structures such as the foundation and subsea cables.
>
> Cougar-XTi can be paired with multiple deployment systems, including a tether management system with 200 m of fiber optic tether to work at depth. The ROV can also be operated as a free-swimming device, for which it uses thrusters to navigate and manoeuvrer underwater. Use of this ROV rather than divers reduces cost and safety risk to personnel.
>
> Refer to **Register 7** of the workbook for details related to other commercially available AWL and BWL technology that can perform maintenance, testing and repairs.

3.8 RT under development for inspection, maintenance, testing, and repairs (Register 8)

New technologies are under development to enhance and expand the capabilities of remote operations, including crawlers, drones, UUVs (including AUVs and ROVs), robotic arms, autonomous platforms, monitoring sensors, corrosion protection systems, digital twins, virtual reality systems, machine learning algorithms, and data processing frameworks. These future technologies and enhancements are in various phases of development, ranging from the initial phase of acquiring grant funding to the near-commercialization phase of prototype demonstration in offshore testing facilities. DNV documented RTs under development in the accompanying **Remote Technologies Register** workbook**,** sheet "**Register 8**", and summarized below.

Well-established devices, like crawlers, drones, and UUVs, will benefit from ongoing innovation efforts through enhanced agility and autonomy. Underwater vehicles, for instance, are being developed to mimic the movement of fish more closely, allowing for greater precision and higher agility for operations performed in proximity to structures. [6] In particular, these devices are being enhanced to support operations while navigating around curved structures and under a wide range of flow conditions. Additionally, both above-water and below-water technologies are being integrated into autonomous systems, such as landing platforms, deployment systems, and charging stations. Landing platforms will be used to deploy drones and crawlers that will either autonomously perform tasks or transfer tools and materials to technicians performing these tasks manually. Deployment systems are being designed as autonomous platforms that will transport, deploy, and provide power to underwater vehicles, essentially acting as hubs or “motherships” at offshore sites. Charging stations are also being developed for underwater vehicles with the intent of providing both shelter and power to these devices on a permanent basis.

Digital innovations are also poised to transform the industry through techniques in data processing, machine learning, artificial intelligence, numerical modelling, and virtual reality. These techniques will be informed by data from a variety of sources, including in-person inspections, condition monitoring, SCADA signals, asset design and construction information, and environmental surveys. One such digital product is the “digital twin”, which combines real-world operational data with numerical modelling, artificial intelligence, and machine learning techniques to improve asset management. Digital twins act as 2D or 3D digital representations of real-world assets, such as wind turbines and floating foundations, at offshore sites. Through digital twins, operators are able to garner real-time insights on the condition of their assets and identify potential impacts and hazards. This holistic view of the condition and performance of offshore assets will support RBI planning, thereby reducing unplanned downtime and improving asset reliability and worker safety.

Register 8 summarizes the capabilities under development of physical devices and digital products to conduct maintenance, testing, and repair operations. For each identified product, the register provides the following information:

- Name of manufacturer, service provider, or operator of equipment
- Name and type of equipment
- Status of development
- Detailed description of equipment and technical specifications, including equipment dimensions, weight, operating heights (above water) or depths (below water)
- Payload tools that support maintenance, testing, repairs, and inspection activities
- Deployment method and location
- Components that may be managed using the equipment
- Details regarding equipment capabilities for maintenance, testing, and repairs
- Level of autonomy, where 1 = human hand-operated, 2 = human-operated remotely, 3 = fully autonomous, i.e., no human intervention once deployed, and 4 = other
- Level of use for activities related to the wind turbines, both onshore and offshore
- Safety impacts of the use of equipment compared to manned inspection methods
- Benefits, challenges, and risks associated with the use of equipment

Spotlight on Submersible Deployment Platforms

The **Register 8** sheet in the **Remote Technology Register** workbook includes the remote technologies under development that support inspection, testing, and/or repair operations. The autonomous platforms or "motherships", Ridley and Loggerhead, which are detailed in Row 17 of **Register 8**, are spotlighted here as an example of the type and scope of information provided in the register.

HonuWorx, a subsea robotics company, is developing a series of submersible deployment systems ("motherships") for remotely operated worker vehicles, such as AUVs and ROVs. Ridley, the first robotic system in this series of technologies, is a semisubmersible platform that transports, deploys, and retrieves worker vehicles at the offshore site. Ridley will pave the way for the Loggerhead concept, a similar deployment platform that will offer the additional capability of acting as a mobile power and communications hub for worker vehicles.

Ridley and Loggerhead can be towed to the work site, where these systems can then conduct submerged deployments of worker vehicles for the inspection, testing, and/or repair of structures under the water line and/or in the splash zone. Since these platforms are approximately 15 m in size, small vessels can be used to tow them to the work site. Missions can be remotely supervised, monitored, and coordinated in real time by onshore support teams using cloud-based mission control and automation software.

The deployment of worker vehicles using submersible systems, like Ridley and Loggerhead, benefits from the reduced risks associated with traditional crane-based deployments. The cost and carbon footprint associated with deployment from large vessels are eliminated. Safety risk to offshore crews and downtime/delays associated with heavy weather are diminished. Still, operators must recognize that any downtime of these mothership technologies may disrupt the operation of dependent worker vehicles.

The capabilities of the Ridley system will be tested and validated at Offshore Renewable Energy (ORE) Catapult's test facilities.

Refer to **Register 8** of the workbook for details related to other AWL and BWL remote technology under development.

3.9 Best practices for documenting results of RT (Register 9)

Efficiently using results generated by remote inspection, maintenance, testing, and repair can be challenging as the type and quantity of data may be difficult to integrate into existing reporting systems. Tackling this challenge by mining the data using ML and AI methods as well as standardizing and automating remote inspections reporting is key to successfully integrate new remote technologies to the inspection, maintenance, testing, and repair processes. DNV therefore recommends applying a data ccience approach, which is detailed in the accompanying **Remote Technologies Register** workbook, sheet **Register 9**, **Part 1**, and described below in Section 3.9.1. A representative list of programs and tools for handling data from remote systems is provided in **Register 9, Part 2** and described below in Section 3.9.2.

3.9.1 Part 1: Critical features of a documentation gathering and data management for RT systems

Given the large data sets that can be generated through RT measurement campaigns, and the need to aggregate, validate, process and disseminate (report) the results in the desired format and at the required frequency, **Register 9, Part 1** outlines a data science approach to data management, where the ultimate goal is to develop the necessary software tools to auto-generate the required annual BSEE Self-Inspection Report outlined in 30 CFR 585.824 as well as mine the data and employ artificial intelligence (AI) to improve maintenance, system monitoring, and safety beyond the regulatory requirements for self-inspection reports. As a first step, **Register 9, Part 1** defines and describes the Data Science process and outlines the minimum information that will be necessary to include in the BSEE Self-Inspection Report.

The cross-industry standard process (CRISP) for data science [7] has six main parts (Figure 3-2): A) business understanding – understanding the problem to be solved, B) data understanding – getting to know the data and how to acquire it, C) data preparation – cleaning the data to make it fit for purpose, D) modelling – building analytical models from the prepared data, E) evaluation – evaluating carefully whether the model meets the performance and purpose demanded, and F) deployment – deploying the model into a digital solution/interface and/or report. It should be noted that this is not a linear process, but an agile process with multiple iterations of exploration and trial-and-error with continuous improvement.

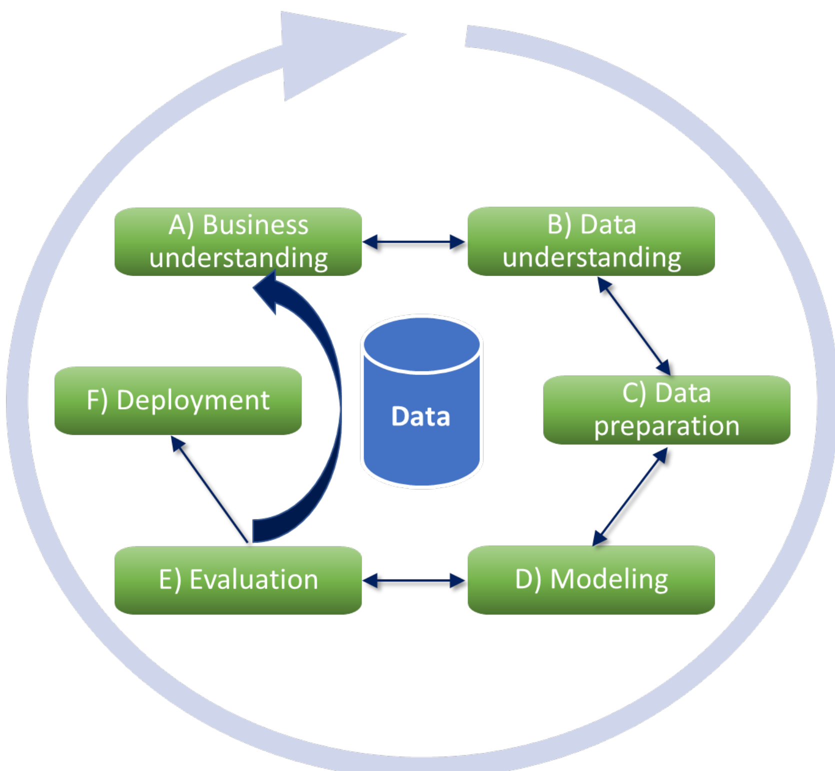

Figure 3-2 The cross-industry standard process (CRISP) for Data Science

The Data Science work process begins with an understanding of a project's needs and requirements from a business perspective, as depicted in Figure 3-2. For offshore wind farms, operators are required to ensure the structural and functional integrity of offshore assets and the safety of personnel conducting offshore operations. Those offshore assets that can be inspected remotely, as detailed in Section 3.3, must be inspected for existing and potential damage at inspection intervals as outlined in Section 3.5. While in-person operations have traditionally been relied on for the inspection of critical systems, remote monitoring methods (Section 3.1: Register 1) and remote inspection technologies (Section 3.2: Register 2) are increasingly being considered for such operations. Generally, these methodologies and technologies serve as safer, more cost-effective, and less time-intensive alternatives when suitable for carrying out inspection, maintenance, testing, and repairs as described in Sections 3.2 and 3.7. In fact, ongoing innovations are set to enhance the capabilities of existing technologies and to create new solutions, both through physical and digital systems and tools, as outlined in Section 3.8. Digital tools, in particular, are expected to advance the industry's efforts toward data-driven insights and a predictive approach to maintenance and repairs.

A clear understanding of the business needs of a project leads to a more informed and intentional approach to data collection (Figure 3-2: B), especially in support of digital systems and tools. The useful and efficient implementation of digital systems heavily relies upon the quantity and quality of the available data. While data intended for use in complex algorithms and data-driven models must be fit for purpose, the available data is typically derived as a by-product of control and monitoring systems. Therefore, the first step in data acquisition is to identify and invest in frameworks and tools that will collect sufficient, high-quality data suitable for analysis, modelling, and automation.

The data collected must then be prepared with robust and tested procedures for storage, security, handling, processing, cleaning, and quality assurance (Figure 3-2: C). Data is increasingly being stored in 'The Cloud', a collection of remote servers that allows for easier access to large quantities of data and greater opportunities for collaboration and processing. Handling procedures are also implemented to ensure that the available data is appropriately protected and encrypted based on the associated sensitivity level. The available data is then processed and cleaned with techniques and infrastructure suitable for its volume and structure. 'Big Data' processing systems, which offer high ingestion rates and parallel computing capabilities, are necessary. Once the data has been cleaned and processed, it must be assessed with respect to the level of quality required for its intended use. High-quality data is precise, complete, and reusable, and it will meet basic quality standards like ISO 8000 "Data Quality and Enterprise Master Data".

High-quality data is an input in data-driven modelling methods (Figure 3-2: D), such as machine learning, deep learning, and big data techniques. The choice of technique depends on the goal of the analysis and the desired outputs and insights. Machine learning, a subset of artificial intelligence, uses data to train complex algorithms in order to predict trends and calculate the probability of particular conditions. Deep learning, a subset of machine learning, uses deep neural network models, which can be used to train and improve the accuracy of visual inspection systems. Additionally, Big Data processing encompasses the set of techniques and models used to implement parallel processing and high-performance computing on large volumes of data.

The effectiveness of the chosen data-driven model is then evaluated on the basis of the model's ability to meet the business objectives (Figure 3-2: E). A model will be considered for deployment if it is useful in deriving the desired insights or solutions for the business objectives (Figure 3-2: F). Otherwise, the Data Science work process is re-initiated, now informed by the lessons learned from the exercise. This cycle is a reflection of the iterative process required to derive insights for decision-making from vast amounts of complex data.

Data for the purpose of understanding the operational performance of offshore assets is collected through remote systems and sensors installed on the wind turbines and foundations, such as CMS, SCADA sensors, and strain gauge sensors (among others). Environmental data can also supplement the analysis and modelling of loads experienced by offshore assets and the potential forms and levels of degradation (e.g., determining fatigue loading cycles). Remote inspection technologies are also being employed for the collection of measurements, images and video through inspection, monitoring, and testing methods. The data collected from various sources is increasingly being integrated into dashboards and automated modelling systems to generate real-time insights and forecasts on the condition of offshore assets. Digital products offering such capabilities serve risk-based inspection and predictive maintenance planning through damage detection and prediction with techniques in artificial intelligence, machine learning, data mining, data analytics, and automated reporting.

3.9.2 Part 2: Predictive maintenance programs/tools employing data from remote monitoring systems, with examples

Part 2 of **Register 9** provides a representative list of programs and tools for processing large data sets from remote monitoring or RT campaigns. These programs integrate data processed through artificial intelligence, digital twins, machine learning, and other such models and techniques into work order systems and collaborative software platforms to support automated analytics and reporting. The integration of data-driven technologies with online tools enables informed decision-making and streamlines the reporting process. Some of these systems are commercially available for wind energy applications, and others are under development with potential applications in offshore wind.

The IRIS Data Platform by InterSystems (row 35 of **Register 9**) is an example of a data management system capable of collecting data from monitoring, inspection, digital twin, or other RTs regardless of format, from offshore wind turbine, substructure or OSS RT or CMS in real-time to aggregate, clean, backup, process and transform the information into the desired reporting format, such as BSEE's annual Self-Inspection report.

Spotlight on WindGEMINI

The **Register 9** sheet in the **Remote Technology Register** workbook includes two parts. Part 1 details the critical features of a documentation gathering and management system based on a Data Science approach. Part 2 provides a list of systems that process large volumes of data for streamlined analytics and reporting. WindGEMINI, detailed in Row 5 of Register 9: Part 2, is spotlighted here as an example of the type and scope of information provided in the register for integrated data systems.

WindGEMINI is a wind turbine digital twin developed by DNV for the purpose of enabling data-driven insights to reduce costs, extend life, and maximize production of a wind farm. WindGEMINI uses data from wind farms, such as SCADA signals from wind turbines, as input for real-time analysis and forecasting. This input data is analysed by WindGEMINI's advanced analytics system to identify fatigue accumulation on structural components, performance patterns indicative of potential failures, shifts in the turbine power curve, and issues that may lead to reduced energy capture and/or turbine life. These analyses inform wind farm operators on turbine performance, energy production, and turbine health and remaining life, and facilitate maintenance planning and optimization.

WindGEMINI offers a single, integrated solution for gaining real-time and forecasted insights on the performance and condition of wind turbines. The system provides 24/7 access to key metrics and advanced analytics. The insights gained from the use of WindGEMINI reduces unplanned downtime, unscheduled maintenance and inspections, and the likelihood of catastrophic failures.

WindGEMINI is commercially available and has been implemented in more than 33 wind farms.

Refer to **Register 9** of the workbook for details other predictive maintenance programs and tools.

4 SUMMARY OF RESULTS

4.1.1 Potential economic benefits of RT

This study included a qualitative assessment of potential economic benefits of remote technologies. RTs can provide significant economic benefits through operation cost savings, time savings, reduction of risk to personnel, and early failure detection. For example, exterior inspection of blades using drones deployed from nearby vessels saves time by eliminating the need for personnel to transfer to the turbine, climb the tower, and rappel down the blade from the nacelle. Shorter inspection time reduces turbine downtime and potential energy production losses. Inspections via drone or crawler can also reduce the need to hire multiple crew members and cranes to service blades, further reducing costs. Drone service providers report operational cost savings of between 35% and 80% compared to manual when conducting blade inspection, cleaning, and LPS testing. Cost savings of up to 50% in defect marking and categorization are reported.

Below water RTs also bring economic benefits. UUVs that can perform preventative maintenance and catch early-stage defects can reduce major failures of subsea equipment, saving costs. RT featuring Non-Destructive inspection capabilities reduce the need for technicians to access difficult locations, which in turn reduces costs and allows for a lower frequency of inspection. It may also allow for inspection of components that would not be accessible otherwise (for example, inside the blade tips). RTs with advanced monitoring technology can improve data quality and repeatability, catching details manual monitoring may miss. Many RTs are also capable of operating in harsher weather conditions than humans can handle, extending environmental windows during which inspection and maintenance can occur and resulting in fewer delays. More advanced UUVs are being developed and deployed that can live and operate permanently underwater, reducing the need for expensive surface vessels that are typically required to support remote operations today. These economic benefits can help remove barriers in offshore wind adoption and make offshore wind investment more attractive to developers.

4.1.2 Gaps in regulatory framework for RT

As summarized in Section 3.6, RTs can be employed to meet standards for inspection as detailed in **Register 6** in the accompanying **Remote Technology Register** workbook, either alone or in conjunction with some level of manned activity. However, the regulatory framework concerning remote technologies in general is still evolving and varies for different technologies. This section reviews the regulatory environment for three categories of RT: drones, crawlers and other non-airborne AWL robots, and UUVs (BWL).

Drones (UAS): In Europe, the European Union Aviation Safety Agency (EASA) has developed common rules for drones (UAS), applying the highest safety standards achieved in manned aviation to UAS as well. The aim is to “strike a balance between the obligations of drone manufacturers and operators in terms of safety, respect for privacy, the environment, protection against noise, and security.” [8] In the U.S., small UAS (less than 55 pounds) are regulated by the FAA under USA Regulations (Part 107). [9] UAS are required to be registered with the FAA and the pilot must hold a certificate with a small UAS rating. UAS greater than 55 pounds are not included in the FAA rules for commercial or recreational UAS, representing a potential regulatory gap that may be inhibiting development of larger drones that could be used for offshore wind maintenance.

Robots and robotic crawlers: Given the safety issues related to working offshore, robots and automation in general are increasingly being implemented to reduce both the number of technicians and total time they need to be deployed offshore. Currently there is significant innovation happening in the development of robot technologies to address inspection and maintenance of a given component or subsystem on the turbine or offshore substation. As technologies and robotic solutions mature, a move toward standardization of infrastructure could help increase their utility, contributing to reducing the overall cost of offshore wind. Such standardization is unlikely with OEMs, developers, and operators working to develop solutions on their own. It's possible that the right regulatory framework (e.g., performance-based), could fill that standardization gap for the benefit of the entire U.S. offshore wind industry.

UUVs: As more WTGs are deployed off the coasts of US waters, UUV traffic will inevitably increase as RT is increasingly used for inspections, maintenance and other BWL duties as described in this report. The global UUV market is growing rapidly and expected to exceed the $5 billion mark by the end of this year. Every vessel must obey the same International or Federal navigation rules for preventing collisions at sea. The U.S. Coast Guard is the agency with legal authority to enforce these rules in U.S. waters. However, the governing rules were created for surface ships, submarines, and aircraft with humans on board. Example gaps in the regulatory framework regarding UUVs include:

- Currently there is no controlling definition of what constitutes a "vessel" and whether UUVs are included
- If UUVs are vessels, Rule 5 of the International Regulations for Preventing Collisions at Sea (COLREGs) requires vessels to have a lookout to prevent collisions. Do acoustic and visual capabilities or other obstacle avoidance measures of UUVs that minimize interference with vessels or fishing activities such as drag netting or pots satisfy Rule 5?
- Rule 2(b) of the COLREGs allow an on-board master or crew, in the case of an emergency, "to make a departure from these Rules necessary to avoid immediate danger." For a UUV with no human on board, to whom would the responsibilities apply?
- The Coast Guard national vessel registration process does not explicitly apply to ROVs
- If UUVs are transporting tools or spare parts, applicability of the Jones Act would need to be assessed.

There is generally very little regulatory framework pertaining specifically to UUVs, whether ROVs or AUVs, so operators are left to fill the gaps using existing maritime law and federal statutes. This points to the need for further development of UUV-specific standards by the International Maritime Organization (IMO) to regulate UUVs for the benefit of the offshore wind industry, the fishing industry, shipping, and other maritime activities.

4.1.3 Risk-based inspection framework using RT

Scheduled inspections offer wind farm operators insights on the structural condition of offshore structures. Wind farm operators, however, can apply an RBI framework to complement scheduled inspections. The RBI framework for inspection and maintenance is based on the design life of the system and requires a comprehensive analysis of the system, consistent and reliable feedback from the system by the CMS, which enables planning of inspection and maintenance activities based on the actual condition of the equipment, rather than simply time-based. The CMS monitors the condition of wind turbine components on a continuous basis. The CMS measures parameters such as temperature, acoustic signals, vibrations, electrical effects, dissolved gases, partial discharges, gas bubbling and power generation to monitor the condition of critical components of a wind turbine. These measurements allow for the detection of anomalies and trends indicative of potential system failures. Equipped with this information, wind farm operators are able to prepare for predictive maintenance and repairs. RTs such as drones, crawlers, ROVs, and AUV's can facilitate predictive operations and RBI by conducting general visual inspections as needed. This reduces the need for traditional methods requiring climbers for above-water components and divers for below-water components. Traditional methods of inspection can then be reserved for circumstances that require further examination. Innovative digital tools, such as digital twins, further support RBI, predictive maintenance and repairs by providing insights on the structures' real-time and forecasted condition. The use of RTs for an RBI approach, in conjunction with scheduled inspections as directed by OEMs and industry standards, enable operators to maintain systems at an acceptable level of reliability while mitigating operational costs.

5 CONCLUSIONS

This report presents a thorough survey of numerous aspects of RT as applied to the monitoring and maintenance of offshore wind farms, including monitoring methods, commercially available remote inspection technology, components that can be remotely assessed, summary of remote inspection programs, optimal inspection intervals in conjunction with manned inspections, applicable industry standards for offshore maintenance, RT that can perform maintenance, testing, repairs and/or component replacements as well as remote technologies under development. Finally, the report explores best practices for summarizing results into a report that would meet the requirements of 30 CFR 585.842 Self-Inspection Report in an automated way. Registers of results for the nine topics investigated in this study are summarized in an accompanying **Remote Technology Register** workbook**.**

The study concludes the following:

- The landscape of remote technologies is changing rapidly, with significant innovation occurring in two specific areas: miniaturization of sensors (meaning more sensors/tools can be deployed on a drone, crawler, robot, UUV, etc.) and increasing application of Data Science principles to the processing of RT data (meaning more sophisticated data mining to detect early-stage signs of failures and support maintenance planning).
- Drone technology used to inspect both exterior and interior of components such as rotor blades, tower, tower platform and ancillary structures, and transition piece (AWL) is mature and commercially available, although deployment in offshore wind farms is still in the early stages. This technology onshore has shown significant cost and time savings, which are expected offshore as well.
- Deployment of drones, ROVs and other RT typically requires a vessel to bring them within close proximity to the equipment to be maintained. In some cases, crew transfer to the turbine platform and climbing up to the nacelle is still required to deploy robots for certain tasks (e.g., blade cleaning and maintenance). As yet very few RTs are actually autonomous and capable of being deployed from shore or an underwater charging station.
- UUV technology (including ROVs and AUVs) is mature, robust, and widely used in offshore industries (offshore wind, oil and gas, and maritime), primarily for inspection of BWL infrastructure. Major innovations under development include increasing autonomy and underwater charging, as well as the types of tools/sensors that can be deployed with the vehicle for tasks other than inspection.
- While this study did not include a detailed economic analysis, there is strong evidence that deploying RT for offshore wind operations and maintenance will not only increase safety by reducing the need for technicians to work offshore but will reduce costs, potentially significantly.
- This study found in general, offshore wind standards, rules, guidelines or recommended practices regarding the inspection and maintenance of offshore wind infrastructure can be met by employing RT to the extent feasible and in conjunction with qualified technicians.
- Gaps remain in the regulatory framework for remote technologies related to offshore wind. While the FAA sets requirements for small drones (up to 55 lbs), there are few regulations regarding other types of robots that operate above the waterline. As for below the water line, there is very little regulatory framework pertaining specifically to UUVs, which are expected to increase in number significantly as more OSW projects are built in U.S. waters.

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APPENDIX A – REMOTE TECHNOLOGY REGISTER

The remote technology registers developed for this project are provided below and in the Excel workbook that accompanies this report:

10311530-HOU-XL-01-B RemoteTechnology.xlsx

	Authors	**Verified**	**Approved**	
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Issue:	**Date:**	**Summary**		
A	1-Jul-22	Initial merged workbook of previously delivered individual Registers		
B	15-Aug-2022	Edited for inclusion in as Appendix B in the report. No substantive changes.		

Register 1: Register of remote **monitoring methods**

Explanatory note:

- This register provides a description of the most prevalent and promising remote monitoring methods as applied to offshore wind equipment.
- For unified table and workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

No.	Monitoring Method	Description	Typical Equip-ment	Type (external/ embedded)	Type of equip-ment it applies to	Examples of identifiable failure modes	Advantages (Technical and economic)	Disadvantages / limitations (Technical and economic)	Extent of application in offshore wind industry	Applicable AWL, BWL or both?	Data Format	Data processing method
1)	Visual inspection	Visual inspection of external surface to identify surface condition.	Camera, borescope, endoscope	external or embedded	External visible surfaces of all equipment	*External corrosion *Structural damage, *External degradation/ cracking *Route changes	1) Easily available compared to other inspection methods 2) Photographic evidence can be stored and transferred to experts not at site 3) Most economic compared to other methods. Can be used prior to involving other, more expensive, methods	1) Condition of internal components cannot be assessed. Most of the critical load carrying or functional components are internal and therefore can not be inspected visually. 2) Not as accurate as other inspection tools e.g. MPI, UT 3) Not a preventive tool. It does not provide quantitative information to predict sudden failure in most cases.	Visual inspection of wind systems can be carried out using drones (AWL) and ROVs/AUVs/ submersible drones (BWL)	BOTH	Photos and/or Video	1) Human inspects photos/video, findings logged by hand 2) Machine learning tool inspects photos/video to identify and log anomalies, then human reviews and verifies logged anomalies
2)	Radiograph ic Inspection	X- rays allow inspection of internal components made of materials through which X-rays can travel.		external	Internal component s and metallic sheet thickness	*Structural damage *Fatigue (cracking)	1) Allows inspection of internal components 2) Able to quantify the state of inspected component and its defects	1) Hazardous to handle (source) 2) Requires a detector for which accessibility can be limited to detect internal flaws 3) Results interpretation can be challenging for components with multiple materials 4) Relatively expensive and typically requires manual operation	Limited to above water components and metal sheet thicknesses of hull	Mostly AWL	X-Ray scans	1) Human inspects scans to identify defects, records measurements by hand 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies

3)	Ultrasonic inspection (UT)	Ultrasonic waves transmitted into materials to detect internal flaws or characterize external surfaces as well as internal areas in metallic and non-metallic (e.g., composite) components. Different UT techniques include Pulse Echo UT, Phase Array UT, and Air Coupled UT	portable ultrasonic inspection probe	external	Foundations, moorings, cable system, blades, welds on towers and other structures	*Structural damage, degradation and aging *Insulation damage	1) More accurate than visual inspection. Able to measure thickness. 2) Measurement will quantify the status of failure mode (structural damage), can produce high quality scans of crack/weld issues. 3) Well established Non-destructive inspection method.	1) Expensive 2) Deployment of equipment involved can be challenging offshore 3) Requires post-processing of data and its interpretation (certified technician) 4) Not suitable for certain materials, odd shapes, small objects and rough materials for sound transmission	Underwater or above water inspections of welds and metallic materials of the turbine base can be carried out using ROVs	BOTH	UT Scans, measurements	1) Human inspects scans to identify defects, records measurements by hand 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies
4)	Thermographic inspection	Nonintrusive, usually non-contact inspection technique that involves measuring temperature. Can be used to get a point measurement, or provide a contour map showing temperature variations over an area		external	Electrical (subsea electrical cable)	*Overheating *Insulation damage	1) Provides overall qualitative diagnostics of the conductor or the insulation	1) Relatively expensive 2) Deployment of equipment involved can be challenging offshore 3) Requires post-processing of data and its interpretation (certified technician) 4) Requires further assessment to identify the exact issue 5) Cannot be used for buried/trenched cables	Mostly array cables	BWL	Thermal Imaging Scans	1) Human inspects scans to identify defects 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies
5)	Infrared thermography (IR)	A specific type of thermographic inspection that measures temperature differences to within 0.05 deg C. Provides a contour map showing temperature variations over an area, where thermal signatures may be caused by friction in structural cracks, or changes in air flow	Thermal imaging camera	external	rotor blades, electrical equipment	rotor blades: cracks, delamination, aerodynamic behavior, overheating components	1) Non-destructive 2) Possible deployment on drones	1) Limitations in damage detectability 2) Sensitive to ambient conditions (light and heat)	Limited to above water, blades most likely application	AWL	Thermal Imaging Scans	1) Human inspects scans to identify defects 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies

		such as boundary layer turbulence over a blade.										
6)	Accelerometer	Measures vibrations, detecting specific frequencies related to structures (e.g., natural frequencies) and rotational components (e.g., gear mesh frequencies)	Accelerometers	embedded	gearbox, tower, blades	Structural damage in blades and towers, pitting in bearings, wear in gear teeth	1) Continuous monitoring 2) Mature technology in rotating machinery	1) Less-mature technology for blade and tower structures 2) Requires baseline to be determined 3) Challenges in setting alarm thresholds: detecting damage early enough while avoiding "false positives"	Feasibility likely limited to above water, drivetrain, blades and tower	AWL	Time-series of vibrational signals	1) Digital analysis to detect harmonics 2) Alarms and notifications based on thresholds, shifts in frequency 3) Human intervention in response to alarms / notifications
7)	Acoustic emissions	Measures acoustic signals from an elastic wave (20-1000 kHz) generated by rapid release of energy from within a material. Can be cracking or popping noises due to structural damage, or tonal signals due to air passing over a feature (e.g., on blade surface)	acoustic sensor	external or embedded	Blade interior structure or exterior surfaces	*Damage in blade laminate (cracks, delamination), *Cracks or other damage on blade exterior, particularly on outer spanwise locations where air flow speeds are high	1) Continuous monitoring 2) Relatively inexpensive sensors	1) Low maturity in blade applications 2) Requires baseline to be determined 3) Challenges in setting alarm thresholds: detecting damage early enough while avoiding "false positives"	Little to date	AWL	Time-series of acoustic signals	1) Digital analysis to filter background noise and detect harmonics 2) Alarms and notifications based on thresholds, new signals relative to baseline 3) Human intervention in response to alarms / notifications
8)	Microwave	Detects changes in dielectric constant of materials		external	Blade fiberglass materials	In blade fiber reinforced plastic: broken fibers, voids, disbonds	1) Non destructive 2) Can resolve early stages of damage	1) Newer technology for wind turbine application	Little to date	AWL	Imaging Scans	1) Human inspects scans to identify defects 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies

9)	Fiber optics	Measures strain	glass fiber filaments	embedded	Blades	Allows measurement of deflections correlated with operating conditions, including potential changes relative to baseline operational behavior	1) Continuous monitoring 2) Can be used for turbine control (e.g., for load reduction) and also to detect damage	1) Must be planned-for at the design stage 2) Data requires post-processing and a baseline is needed in order to interpret results 3) Challenges in setting alarm thresholds: detecting damage early enough while avoiding "false positives"	Above water blade monitoring	AWL	Time series of strain signals	1) Digital analysis to compare strain signals with baseline 2) Strains may be computationally integrated to calculate deflections 3) Alarms/notifications based on trending of strains and/or deflections relative to baseline 4) Human action/interventions in response to alarms and notifications
10)	Fiber optics - Optical	Time domain reflectometry to identify anomalies in the fiber optic cable (embedded in subsea cable) along its length	glass fiber filaments	embedded	Subsea cable (Array and export)	*Structural damage, degradation, and aging	1) provides accurate information of cable interruptions, location of joints compared to the baseline 2) no offshore deployment of personnel is required therefore safe method 3) cable integrity can be monitored automatically at predefined intervals or continuously	1) Must be planned-for at the design stage 2) Data requires post-processing and a baseline is needed in order to interpret results	Applicable for subsea cable and components using composite material where it can be embedded	BOTH	OTDR scans	1) Human inspects scans to identify defects, record measurements by hand 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies

11)	Fiber optics - Thermal	Distributed Temperature Measurement System (DTMS) uses the change in optical signal to determine the temperature of the fiber optic and therefore adjacent conductor/cable	glass fiber filaments	embedded	Subsea cable (Array and export)	*Overheating, *Insulation damage	1) provides accurate information of cable interruptions, location of joints compared to the baseline 2) no offshore deployment of personnel is required therefore safe method 3) cable integrity can be monitored automatically at predefined intervals or continuously	1) Must be planned-for at the design stage 2) Data requires post-processing and a baseline is needed in order to interpret results	Applicable for subsea cable and components using composite material where it can be embedded	BOTH	Thermal scans	1) Human inspects scans to identify defects, record measurements by hand 2) Machine learning tool inspects scans to identify and log anomalies, then human reviews and verifies logged anomalies
12)	Strain gauges	Measure state of strain [stress] of a structure using a gauge attached to the structure	strain gauge bridges	embedded	Foundations Moorings Cable system (above water to be filled)	*Structural damage *Fatigue	1) Provides the first hand quantitative information of state of structure exposed to loading 2) Can collect, store and transmit data using pre-installed equipment	1) requires planning from start of operational life and associated cost 2) limited to number of gauges and their location on structure 3) limited service life	Applicable for foundations, moorings and cable system	BOTH	Gauge transmits measurement data over time	1) Data acquisition system is used 2) Machine learning tool inspects data to identify, log anomalies and predict failure, then human reviews and verifies logged anomalies
13)	Digital twin / online monitoring	Virtual model (software tool) designed to accurately reflect a physical system. The tool collects and processes various inspection data to represent the state of the components and predict their behavior.	Computer with digital model of the physical system	external or embedded	All components where inspection data can be obtained	customized for desired failure mode (e.g. fatigue, structural, corrosion etc.)	1) can be developed or expanded to cover a number of failure modes 2) results can be accessed remotely in real time, no human intervention required	1) Relies on the inspection data and training 2) complex system relying on multiple inputs and processing of data 3) requires feedback/confirmation/validation of the inputs	Applicable for all offshore wind components	BOTH	Responses are evaluated internally by the digital twin tool triggering alarms visualized in a control panel	1) Inspection data is processed by the digital twin tool 2) Machine learning process identifies and logs anomalies and predicts failure, then human reviews and verifies logged anomalies

14)	Magnetic flux leakage	Magnetic field applied to external post-tensioned tendons, metallic cables, steel structures to detect location and extent of corrosion	Permanent magnets, magnetometer	external	post-tensioned tendons, metallic cables, steel structures	corrosion, breakage of cable strands, pitting	1) NDE technique 2) Can detect several failure modes 3)		Metal anchor cables, post-tensioned tendons in concrete structures (foundations, floaters), steel structures	BOTH	Incidents of flux leakage show up in scan of magnetized component, indicating where damage has been detected.	
15)	Coupon inspection	Test coupons are small samples of materials to be tested that are exposed to the environment in operating equipment. They are removed at specified intervals and inspected to monitor structural/material integrity.	Coupons for testing	embedded	BWL: Foundation (material from structures), Moorings, Array or Export Cables (insulation) AWL: Tower, Power cables (insulation)	Corrosion, structural and fatigue damage, degradation, insulation damage	1) Provides the best-quality first hand information	1) involves retrieval/replacement operations offshore 2) limited to number of coupons 3) requires planning from start of operational life	Applicable for foundations, moorings, cable system (array and export), towers, power cables	BOTH	Physical piece of equipment retrieved where usually destructive examination/ characterization is carried out	1) Additional equipment needed for destructive examination, measurements 2) Typically not automated

Register 2: Register of **commercially available** remote inspection technologies

Explanatory note:

- Provides a description of the most prevalent and promising remote monitoring methods as applied to offshore wind equipment.
- Register has been split into TWO tables (for readability). For unified table and workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 2-1: Columns 1-9

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
#	**Manufacturer/ Service Provider or Operator**	**Equipment name**	**Remote Inspection Technology (RIT) Type**	**Is the equipment in commercial use or under development?**	**Number of years in commercial use**	**If commercial, project references**	**Technical Specifications**	**Installed RIT tools**	**Deployment method and additional equipment required**
ABOVE WATER									
	MANUFACTURERS								
1	ANYbotics	ANYmal	4-legged robot	Commercial	5			IR Camera, HD camera Noise sensor Lidar	auto door opening
2	Boston Dynamics	Spot	4-legged robot	Commercial	5			Camera, IR camera, leak detection, Lidar	auto door opening
3	Superdroid robots	HD2	caterpillar robot with robotic arm	Commercial	3			5-Axis removable arm High intensity LED lights Gripper and rear IR camera	
4	Mitsubishi	EX ROVR	caterpillar robot with robotic arm	Development				Camera, IR camera, leak detection, Lidar	
5	Xocean	USV	Unmanned Surface Vehicle	Commercial	4			Camera, sonar	from shore
6	Bladebug	crawler robot	crawler robot with six independent legs that use suction to maintain connection to the blade surface	Commercial	3			camera, UT NDT, composite repair patch	from nacelle
7	DJI	drone and sensors manufacturer							

8	Rope Robotics	BR8 Robot	Robot hoisted to blade using ropes	Commercial	1	Partnered with major Danish developer, 2021		HD camera, laser scanner, robot arm w/repair capabilities	Ropes deployed from the nacelle lift robot from base platform
9	EddyFi	Magg crawler robot	Small, tethered robot equipped with rare-earth magnets that attach to steel towers	Commercial				360-deg HD video/still camera, laser-guided, ACFM (alternating current field measurement), ECA (Eddy current array testing), and UT.	Deploy from tower base and robot climbs up tower (external inspections) or from inside the blade hub (internal blade inspection)
	SERVICE PROVIDERS								
10	SkySpecs	flying drones	Thermal imaging	Commercial				HD and Thermal camera	from CTV/SOV
11	ABJ	Windvalue	Thermal imaging	Commercial				HD and Thermal camera	from CTV/SOV
12	Aerodyne Measure		Thermal imaging	Commercial				HD and Thermal camera	from CTV/SOV
13	Aerodyne	DT^3	Robotic blade care with AI driven defect detection.				Drones equipped with HD cameras and capability of locking the camera onto target to capture 1 mm/pixel resolution. Crawler lowered via rope from the nacelle or inside the hub.	LPS testing system, blade cleaning tools	Deployed from nacelle or from inside the hub by a technician
14	Precision hawk	Drone	Thermal imaging	Commercial				HD and Thermal camera	from CTV/SOV
15	Apellix		UT	Commercial				UT sensor	from CTV/SOV
16	Skyline Drone		UT	Commercial				UT sensor	from CTV/SOV
17	Wind Power Lab		small drone	Commercial				RGB camera	from hub
18	Blade Edge		RGB camera	Commercial				HD camera	from CTV/SOV
19	Drone Base		Thermal imaging	Commercial				HD and Thermal camera	from CTV/SOV
	BELOW WATER								
20	International Submarine Engineering Ltd (ISE)	EXPLORER	AUV	Commercial		Arctic Explorer, Delivered to: Ifremer (France, 2), NOAA (USA), and several international Coast Guards	Depth: 3,000 m, 6,000 m Energy: 18-48 kWh rechargeable battery Weight: 620-1700 kg	*can be equipped with any sensor designed for use on an AUV	lowered from a vessel, supply boat

21	L3Harris Technologies, Inc.	IVER4 580	UUV	Commercial			Depth: 200 m, 300 m Energy: 780 Watt-hr Li-Ion rechargeable battery section; future 2 kWh Li-Ion rechargeable battery section Weight: < 100 lbs.	*full sensor suite in forward-sealed section including side scan sonar, inertial navigation system, sound velocity probe and doppler velocity log	handheld deployable, lowered from a vessel
22	L3Harris Technologies, Inc.	IVER4 900	UUV	Commercial			Depth: 300 m Energy: 2 kWh NiMH rechargeable 20+ Hrs, 4 kWh Li-Ion rechargeable 40+ Hrs, 3 kWh primary alkaline 30+ Hrs, Aluminum-Water power for 80+ Hrs Weight: < 230 lbs.	*full sensor suite including side scan sonar, inertial navigation system, sound velocity probe and doppler velocity log	~handheld deployable, lowered from a vessel
23	Kongsberg Maritime	HUGIN (1000, 3000, 4500)	AUV	Commercial	Since early 2000's	"HUGIN AUVs have surveyed most of the major deepwater offshore oil and gas fields world wide...Field operations have taken place world wide from arctic to tropical areas. More than three times around the equator in line kilometers of commercial work was already accumulated by 2006."	Depth: 1,000 m, 3,000 m, 4,500 m Energy: 15 kWh, 45 kWh, 60 kWh Weight: 650-850 kg, 1400 kg, 1900 kg	*MBE, SSS, SBP, CTD, ADCP, + others	launched from vessel
24	Kongsberg Maritime	HUGIN Superior	AUV	Commercial			Depth: 6,000 m Energy: 62.5 kWh pressure tolerant lithium polymer battery Weight: 2,200 kg	*comprehensive suite of payload sensors	launched from vessel
25	Oceaneering International, Inc.	Freedom	ROV	Commercial			Depth: 6,000 m Energy: 50 - 100 kWh battery capacity Weight: 2,200 - 2,700 kg	*suite of optional sensors / tools	launched from vessel
26	Hydroid (a Kongsberg company)	REMUS 100	AUV	Commercial			Depth: 100 m Energy: 1.5 kWh Li-ion battery Weight: 36 kg	*suite of optional sensors / tools	launched from vessel

27	Hydroid (a Kongsberg company)	REMUS 600	AUV	Commercial			Depth: 600 m (1,500 m possible) Energy: 5.4 kWh Li-ion battery Weight: 220 - 385 kg	*suite of optional sensors / tools	launched from vessel
28	Hydroid (a Kongsberg company)	REMUS 6000	AUV	Commercial			Depth: 6,000 m Energy: 12 kWh Li-ion battery Weight: 862 kg	*suite of optional sensors / tools	launched from vessel
29	L3Harris Technologies, Inc.	IVER3 EP	AUV	Commercial			N/A	?	launched from vessel
30	General Dynamics Mission Systems	Bluefin-9	UUV	Commercial			Depth: 200 m Energy: 1.9 kWh Li-ion battery Weight: 70 kg	*integrated suite of sensors	Two-Man Portable
31	General Dynamics Mission Systems	Bluefin-12	UUV	Commercial			Depth: 200 m Energy: 4x 1.9 kWh Li-ion batteries Weight: 250 kg	*integrated suite of sensors	launched from vessel
32	ECA Group	A9, A18, A3000	AUV	Commercial			N/A	?	Various
33	ECA Group	A9-E	AUV	Commercial			Depth: 200 m Energy: 2.1 or 4.2 kWh Weight: 70 or 100 kg	*Interferometric Side Scan Sonar, Video, CTD, environmental sensors (e.g. turbidity, PH, DO or fDOM)	?
34	ECA Group	H2000	ROV	Commercial			Depth: 2,000 m Energy: 40 kVA required Weight: 900 kg	*variety of viewing & navigation systems and sensors	deployed from vessel
35	SAAB	Sabertooth	AUV IMR Platform				Depth: 1,200 m or 3,000 m Max. Weight: 800 kg (single hull), 2000 kg (double hull) Battery: 12kWh (single hull), 30 kWh (double hull)	Cameras, sonars, HV tooling/motor	Underwater docking system
36	SAAB	Seaeye Tiger	AUV	Commercial			Depth: 1000 m Weight: 150 kg	Cameras, sonar, cleaning brush, compact cutter, ultrasonic thickness gauge	
37	4Subsea	SMS Strain Sensor; SMS Guard; SMS Motion; 4Insight (ML data analysis)	sensor	Commercial	<1			strain sensors, IoT enabled	Installed by technician on WTG (above water), or ROV or diver (below water)
38	Offshore RE Center (ORE)	iFrog	crawler robot	Development				Camera, water-jet cleaning	Lowered into monopile or transition piece

Register 2-2: Columns 1, 10-17

	1	10	11	12	13	14	15	16	17
#	**Manufacturer/ Service Provider or Operator**	**Inspect-able offshore wind structures**	**Capabilities: * inspect * test * repair**	**Level of autono my (refer to "Reg 2 Notes")**	**Used for WT? (0=none, 5=exten-sive)**	**Used for offshore WT? (0=none, 5=exten-sive)**	**Economic Benefits**	**Associated Risks**	**Advantages compared to manual inspection**
ABOVE WATER									
	MANUFACTURERS								
1	ANYbotics		Inspect (gauge reading, IR, sound, Lidar measurement)	3	2	2			
2	Boston Dynamics		Inspect (gauge reading, IR, Lidar measurement)	3					
3	Superdroid robots		Inspect, Repair (articulated arm)	3	0	0			
4	Mitsubishi		Inspect		0	0			
5	Xocean	visual inspection of foundations	Inspect (visual, bathymetry)			2			
6	Bladebug	blade repair	Inspect (visual, NDT), Test (UT), Repair (composite repair)		2	0		Risk to technicians transferring from CTV to tower platform; if suction fails, robot could fall creating a 'fall from heights risk	
7	DJI		Inspect (thermal, FLIR, RGB)						
8	Rope Robotics	blade surface, esp. leading edge	Inspect, Clean, Sand, Repair (articulated arm)	2	5	3		if robot loses contact with blade, swinging robot could cause damage	Eliminates need for rappelling down the blade for inspection and/or leading edge repair
9	EddyFi	tower, blade external (robot has partial access to view rotor blades) and internal	Inspect tower, blades, generator, Testing (NDT)		4	3		If robot loses contact with tower, could fall to the tower base and cause damage.	Reduces need to rappel down blades to inspect. Potentially eliminates need to rappel down the tower to inspect.
	SERVICE PROVIDERS								
10	SkySpecs	blade coating inspection	Inspect, Test (IR, RGB)		5	0		loss of drone	

11	ABJ	blade coating inspection, damage detection	Inspect, Test (IR, RGB)		5	0		loss of drone	
12	Aerodyne Measure	blade coating inspection	Inspect, Test (IR, RGB)		5	0		loss of drone	
13	Aerodyne	blade exterior and interior	Inspects blade exterior (drone) and interior (robotic crawler).		2	5	Aerodyne reports operation cost savings of 35%, and 50% cos saving in defect marking and categorization.		eliminates need to rappel down the blade exterior or enter the blade (confined space) for internal inspection.
14	Precision hawk	blade coating inspection	Inspect, Test (IR, RGB)		5	0	Reduces inspect. Cost by up to 80% over manual.	loss of drone	reduces climbs by up to 50%
15	Apellix	blade, tower, OSS	Inspect (UT thickness), Test		3	0			
16	Skyline Drone	blade, tower, OSS	Inspect (UT thickness), Test		3	0			
17	Wind Power Lab	internal blades	Inspect (inside blades)		3	1			Minimizes need for confined space entry
18	Blade Edge	blade coating inspection	Inspect (visual)		5	0			
19	Drone Base	blade coating inspection	Inspect, Test (IR, RGB)		5	0		loss of drone	
BELOW WATER									
20	International Submarine Engineering Ltd (ISE)	*all possibilities	Survey, Inspection	3					
21	L3Harris Technologies, Inc.	*external equipment shallower than 200/300 m	Inspection	3					
22	L3Harris Technologies, Inc.	*external equipment shallower than 300 m	Inspection	3					
23	Kongsberg Maritime	*all possibilities	Survey, Inspection	3					
24	Kongsberg Maritime	*all possibilities	Survey, Inspection	3					
25	Oceaneering International, Inc.	*all possibilities	Survey, Inspection, Light Intervention	2					
26	Hydroid (a Kongsberg company)	*external equipment shallower than 100 m	Survey	3					
27	Hydroid (a Kongsberg company)	*external equipment shallower than 600 m	Survey, Inspection	3					
28	Hydroid (a Kongsberg company)	*all possibilities	Survey, Inspection	3					

29	L3Harris Technologies, Inc.		Inspection	3					
30	General Dynamics Mission Systems	*external equipment shallower than 200 m	Inspection	3					
31	General Dynamics Mission Systems	*external equipment shallower than 200 m	Survey, Inspection	3					
32	ECA Group		Survey, Inspection	3					
33	ECA Group	*external equipment shallower than 200 m	Inspection	3					
34	ECA Group	*all possibilities	Inspection, Intervention	2					
35	SAAB	all possibilities	Inspection, Maintenance, Repair (IMR)	2 or 3					
36	SAAB	all possibilities	Inspection	2 or 3					
37	4Subsea	WTG tower	Can be coupled to SMS Gateway (topside) or SMS Motion (subsea) to provide synchronized strain & motion data	3 (after it's deployed)		3	reduces inspection costs	If sensor fails, then operator lacks real-time loads data	Reduces need for in-person inspection both AWL and BWL
38	Offshore RE Center (ORE)	monopile	* inspect * clean	2	3	4	reduces inspection and cleaning costs		Reduces need for divers into monopile

Column #	Parameter	Description
1	Manufacturer or Operator	Name of the manufacturer or operator
2	Equipment name	Name of the equipment
3	Remote Inspection Technology (RIT) Type	Type of technology e.g. AUV, ROV, Drone, etc.
4	Is the equipment in commercial use or under development?	Project would like to capture information for both current and future equipment; please indicate if the equipment is being used commerically or under development.
5	Number of years in commercial use	If in commercial use, please indicate the number of years the equipment has been used for commercial applications.
6	If commercial, project references	List any project references e.g. location or field, inspected structure types, year etc.
7	Technical specifications	List technical specifications e.g. max. operating water depth, opearting speed, top speed, collision avoidance, range etc.
8	RIT Tools	Any permanent or removable tools that aid inspection e.g. cameras, lights, sensors, scanners, etc.
9	Deployment method and additional equipment required	How is the tool deployed for inspection (self-deployed, launched from vessel etc.) and any additional equipment required for deploying the equipment, e.g. work boat, barge, subsea dock etc.
10	Inspectable offshore wind strutures	Struture types that may be inspected e.g. hulls (internal/external), moorings, cables, subsea equipment, foundation etc.
11	Capabilities	List all capabilities of the equipment e.g. inspection, testing, maintenance, cleaning, repair, etc.
12	Level of autonomy	1 = Human hand-operated e.g. diver tools, 2 = Human-operated remotely, 3 = Fully autonomous i.e. no human intervention once deployed, 4 = other, please specify
13	Used for WT? (0=none, 5=extensive)	
14	Used for offshore WT? (0=none, 5=extensive)	
15	Risks	
16	Benefits	
17	Advantages compared to manual inspection	

Register 3(a): List of **critical components (a) Failure modes**

Explanatory note:

- This register lists critical components of an OSW farm that can be remotely inspected, etc.
- Provides an indication of failure modes each component is subject to.
- Definitions for criticality are provided in the table @ cell B73.
- Register has been split into TWO tables (for readability), where Register 3(a)-1 includes Columns 1-8, and Register 3(a)-2 includes Columns 1,2,9-15. For unified table and workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 3(a)-1: Columns 1-8

	1	2	3	4	5	6	7	8
	System	**Critical components**	**Criticality** 1 = cosmetic, 2 = functional, 3 = major, 4 = catastro-phic	**Corrosion**	**Structural damage**	**Fatigue**	**Lightning**	**Erosion**
	ABOVE WATER							
ROTOR NACELLE ASSEMBLY	Rotor blades	Skin (external). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip.	2		Delamination	X	Lighting Damage	Leading Edge Erosion
		Skin (internal). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip.	2 or 3		Delamination	X	Lighting Damage	
		Spar. Structural element (beam or beams) internal to the rotor blade, often made of epoxy-resin infused layers of carbon fiber for high strength and low weight	3		X	X	Lightning Damage	
		Bolts (blade root)	3		Shear	Fatigue Cracks		
	Rotor hub	Cast iron body	3	X		Fatigue Cracks		
	Main bearing	Races and rollers	2	Pitting		X		
		Cast iron housing	3	X		Fatigue Cracks		
	Mainshaft/Kingpin	Forged or cast body	3			Fatigue Cracks		
	Generator	Direct-Drive windings and magnets	2					
		Direct-Drive rotor and stator housings carry high torque loads	3			Fatigue Cracks		
		Medium-speed windings and magnets	2	X				
		Bearings	2			X		
	Gearbox (not relevant for direct-drive WTGs)	Gears	2	Pitting		X		
		Bearings	2	Pitting		X		
	Generator frame	Main weldment or casting	2 to 3	X	X	X	X	X
	Bedplate	Cast iron body	3	X		Fatigue Cracks		

	Yaw Drive	Yaw motors gearboxes, pinion, bearings, slewrings	2			X		
	Power Electronics	Electrical components	2					
TOWER ASSEMBLY	Tower	Steel	3	Internal and External Corrosion	X	Fatigue Cracks		
		Concrete	3	Internal Rebar Corrosion	X	Fatigue Cracks		
		Hybrid (steel + concrete)	3	Internal Rebar Corrosion and External Corrosion	X	Fatigue Cracks		
		Bolts (tower top, mid, and base flanges)	4	X	X	X		
OFFSHORE SUBSTATION	Offshore Substation Platform	External coating	1	X				
		Internal coating	1	X				
		Above water structure	4			Fatigue Cracks		
		Boat landing	2			Fatigue Cracks		
		Cranes	2	x				
		Transformer	3					
		HV GIS	3					
		HV cables and connectors	3		Mechanical Damages			
		LV electrical cabinets	3		Disconnected Breaker			
		piping	2	X				
		valves	2	X				
		Emergency generators (combination of diesel engine plus electric generator)	2					
		rotating equipment (pumps, chillers, etc.)	2					
	BELOW WATER							
	Foundations	concrete based (GBF)	4	Corrosion of steel elements	Physical Abrasion	X		Chemical Erosion (due to seawater)
		steel structure (monopile, transition piece, jacket)	4	X	Structural damage, shear failure, buckling	X		
		Bolting	3	X	Shear failure	X		
		scour protection material	3					
	Floating hull	concrete based structure (e.g., windcrete concrete spar buoy, BW Ideol concrete barge floater)	4					Chemical Erosion (due to seawater)
		Steel structure (e.g., monopile, tension-leg platform (TLP), spar buoy)	4	X	X			
	Corrosion Protection (CP) System	Anodes	2		X	X		
	Mooring	polyester	4		X	X		Internal abrasion
		ultra-high molecular-weight polyethylene (e.g. Dyneema)	4		X	X		

		chain	4	X	X	Premature rupture due to bending fatigue		
		Anchor piles	4	X	X	Cyclic loading		
	Electrical Cable system	Hangoff assembly	3	X	X	X		
		End connection	3	X	X	X		
		bend stiffener/restrictor	2	X	X	X		
		Subsea cable - Array	3	X	Loss of continuity, shielding losses due to bending	X		Jacket abrasion
		Subsea cable - Export	3	X	Loss of continuity, shielding losses due to bending	X		Jacket abrasion
		Ancillary - Strakes, clamps, buoys	2	X	X	X		
		Cable protection system on seabed	2	X	Shear or winnowing of scour-protection rip-rap	X		
	Offshore substation substructure	Jacket structure	4	X	Structural damage from impact			
		Anodes	2					
		ICCP electrodes	2					
		HJ-Tubes	3					
		scour protection	3					X
		Boat Landing	2	X	Impact Loads	X		

Register 3(a), Table 2: Columns 1,2,9-15

	1	2	9	10	11	12	13	14	15
	System	**Critical components**	**Degradation, aging, cracking**	**Contamination**	**Overheating**	**Insulation damage (Breakdown, Treeing, Partial discharge)**	**Route changes (sediment depletion/accretion, scour, movement of rock cover**	**Human activities (fishing, anchors)**	**Geo-hazards**
	ABOVE WATER								
ROTOR NACELLE ASSEMBLY	Rotor blades	Skin (external). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip.	Skin Crackling						
		Skin (internal). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip.	Crackling						

		Spar. Structural element (beam or beams) internal to the rotor blade, often made of epoxy-resin infused layers of carbon fiber for high strength and low weight	Crackling						
		Bolts (blade root)	Stretching (loosening)						
	Rotor hub	Cast iron body	Extreme Load Cracking						
	Main bearing	Races and rollers	White Etch Cracking						
		Cast iron housing	Extreme Load Cracking						
	Mainshaft/Kingpin	Forged or cast body	Extreme Load Cracking						
	Generator	Direct-Drive windings and magnets		X	Insulation breakdown from high temps and voltages				
		Direct-Drive rotor and stator housings carry high torque loads							
		Medium-speed windings and magnets		X	Insulation breakdown from high temps and voltages				
		Bearings		X	X				
	Gearbox (not relevant for direct-drive WTGs)	Gears		X	X				
		Bearings	White Etch Cracking	X	X				
	Generator frame	Main weldment or casting	X	X	X	X	X	X	X
	Bedplate	Cast iron body	Extreme Load Cracking						
	Yaw Drive	Yaw motors gearboxes, pinion, bearings, slewrings							
	Power Electronics	Electrical components			Breakdown from High temperatures, over voltage				
OFTOWER ASSEMBLY	Tower	Steel	Extreme Load Cracking						
		Concrete	Extreme Load Cracking						
		Hybrid (steel + concrete)	Extreme Load Cracking						
		Bolts (tower top, mid, and base flanges)	Loosening						
ES		External coating							

	Offshore Substation Platform	Internal coating							
		Above water structure		Ship Impact					
		Boat landing		Ship Impact					
		Cranes	Mechanical Wear Down						
		Transformer		Oil Contamination		Partial discharge, connectors fault			
		HV GIS		SF6 Leak		Partial discharge, insulation fault			
		HV cables and connectors			X	Partial Discharge			
		LV electrical cabinets			X				
		piping		Leak, clogged filters					
		valves		Leak					
		Emergency generators (combination of diesel engine plus electric generator)	Bearing Wear Down	Oil Leak	X	Electrical Faults			
		rotating equipment (pumps, chillers, etc.)	Bearing Damage or Wear		X				
	BELOW WATER								
	Foundations	concrete based (GBF)							X
		steel structure (monopile, transition piece, jacket)	Grout failure						X
		Bolting	Stretching (loosening)				Pile pull-put		
		scour protection material					Shifting due to currents		
	Floating hull	concrete based structure (e.g., windcrete concrete spar buoy, BW Ideol concrete barge floater)							
		Steel structure (e.g., monopile, tension-leg platform (TLP), spar buoy)							
	Corrosion Protection (CP) System	Anodes	Premature or excessive degradation						
	Mooring	polyester	X					X	
		ultra-high molecular-weight polyethylene (e.g. Dyneema)	Creep rupture						
		chain						X	
		Anchor piles	Creep					X	X
	Electrical Cable system	Hangoff assembly	X						
		End connection	X					X	
		bend stiffener/restrictor	X						
		Subsea cable - Array	Jacket swelling/cracking		X	Insulation damage	X	X	

		Subsea cable - Export	Jacket swelling/cracking		X	Insulation damage	X	X	X
		Ancillary - Strakes, clamps, buoys	X						
		Cable protection system on seabed	X				Insufficient burial depth	X	X
	Offshore substation substructure	Jacket structure							
		Anodes	Premature or excessive degradation						
		ICCP electrodes							
		HJ-Tubes							
		scour protection							
		Boat Landing							

Criticality Rating	**Definition**
1. Cosmetic	e.g., minor damage that does not impact operation; timing of repair non-critical
2. Functional	e.g. could stop turbine from operating. Could degrade performance
3. Major	e.g., loss of blade, gearbox failure, subsea cable failure
4. Structural	e.g., catastrophic, primary load path, loss of asset

Register 3(b): List of critical components (b) Methods of monitoring or inspection

Explanatory note:
This register lists critical components of an OSW farm that can be remotely inspected, etc.
Provides an indication of which remote inspection and/or monitoring methods are relevant for each component.
Definitions for criticality are provided in the table at the end of this section.

Register has been split into TWO tables (for readability), where Register 3(b)-1 includes Columns 1-9, and Register 3(b)-2 includes Columns 1,2,10-17. For unified table and workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 3(b)-1: Columns 1-9

	1	2	3	4	5	6	7	8	9
	System	**Critical components**	**Criticality** 1 = cosmetic, 2 = functional, 3 = major, 4 = catastrophic	**Visual inspection**	**Radiographic Inspection**	**Ultrasonic inspection**	**Thermographic inspection**	**Infrared (thermography)**	**Acceleration (vibration)**
	ABOVE WATER								
ROTOR NACELLE ASSEMBLY	Rotor blades	Skin (external). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip	2	- visual detection of damages - drone with camera - Automated image analysis		From exterior surface		From ground or instrumented drone, localized temperature rise at defects	
		Skin (internal) Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip	2 or 3	- visual detection of damage - crawler with camera - Automated image analysis		From exterior surface		From hub or instrumented drone, localized temperature rise at defects	
		Spar. Structural element (beam or beams) internal to the rotor blade, often made of epoxy-resin infused layers of carbon fiber for high strength and low weight	3	- visual detection of damage - crawler with camera - Automated image analysis		From exterior surface		From hub or instrumented drone, localized temperature rise at defects	
		Bolts (blade root)	3	It may be possible to detect loosening using torque check marks from drone or crawler images		In-service bolt inspections using "phased array ultrasonic detection technology": https://www.ndt.net/se			

						arch/docs.php3?id=254 67			
	Rotor hub	Cast iron body	3	Crawlers with cameras may be able to detect visible cracks		Potential deployment by crawlers but not yet commercially demonstrated			Monitoring of pitch system "effort", if hub flanges at blades have deformed, pitch action may get hung up or require more force than usual
	Main bearing	Races and rollers	2	Borescope to locate pitting or cracking in races and rollers					Current standard practice
		Cast iron housing	3	Drones and/or crawlers with cameras may be able to detect visible cracks		Potential deployment by crawlers but not yet commercially demonstrated			Displacement sensors might be able to detect unexpected deformations
	Mainshaft / Kingpin	Forged or cast body	3	Crawlers with cameras. Fretting corrosion at main bearing a potential issue that could be identified through feature detection of images using machine learning.		Potential deployment by crawlers but not yet commercially demonstrated			Frequency monitoring
	Generator	Direct-Drive windings and magnets	2	Borescope					
		Direct-Drive rotor and stator housings carry high torque loads	3	Crawlers with cameras		Potential deployment by crawlers but not yet commercially demonstrated		Possibly	Frequency monitoring
		Medium-speed windings and magnets	2					Possibly	
		Bearings	2	Borescope to locate pitting or cracking in races and rollers					Current standard practice
	Gearbox (not relevant for direct-drive WTGs)	Gears	2	Borescope to locate pitting or cracking in gears					Current standard practice
		Bearings	2	Borescope to locate pitting or cracking in races and rollers					Current standard practice
	Generator frame	Main weldment or casting	2 to 3	Crawlers with cameras may be able to detect visible cracks		Potential deployment by crawlers but not yet commercially demonstrated			Monitoring of pitch system "effort"
	Bedplate	Cast iron body	3	Crawlers with cameras may be able to detect visible cracks		Potential deployment by crawlers but not yet commercially demonstrated			Monitoring of pitch system "effort"
	Yaw Drive	Yaw motors gearboxes, pinion, bearings, slew rings	2						

	Power Electronics	Electrical components	2				Possibly	Possibly	
TOWER ASSEMBLY	Tower	Steel	3	Drones and/or crawlers with cameras may be able to detect visible cracks		Potential deployment of UT inspection by crawlers but not yet commercially demonstrated			Frequency monitoring
		Concrete	3	Drones and/or crawlers with cameras may be able to detect visible cracks		Potential deployment of UT inspection by crawlers but not yet commercially demonstrated			Frequency monitoring
		Hybrid (steel + concrete)	3	Drones and/or crawlers with cameras may be able to detect visible cracks		Potential deployment of UT inspection by crawlers but not yet commercially demonstrated			Frequency monitoring
		Bolts (tower top, mid, and base flanges)	4	Drones with cameras may be able to detect bolt loosening if they are properly marked		Phased Array Ultrasonic technology			
OFFSHORE SUBSTATION	Offshore Substation Platform	External coating	1	- visual detection of damage - Automated image analysis					
		Internal coating	1	- visual detection of damage - Automated image analysis					
		Above water structure	4	- Visual identification of cracks, indents, deformations	detection of cracks in critical welds	detection of cracks in critical welds			
		Boat landing	2	- Visual identification of cracks, indents, deformations					
		Cranes	2	Visual identification of cracks, indents, deformation, paint damage - visual check of oil levels					
		Transformer	3	- Reading of local gauges and screens			Detection of over-heated zones or components	Detection of over-heated zones or components	
		HV GIS	3	- Reading of local gauges and screens			Detection of over-heated zones or components	Detection of over-heated zones or components	
		HV cables and connectors	3	- visual detection of over-heated zones - general condition of cable clamps and supports			Detection of over-heated zones	Detection of over-heated zones	

		LV electrical cabinets	3	- Visual identification of breaker status - visual detection of over-heated zones - Reading of local displays			Detection of over-heated zones	Detection of over-heated zones	
		piping	2	- Visual identification of cracks, indents, deformations - detection of leaks					
		valves	2	- detection of leaks - ID of valve position					
		Emergency generators (combination of diesel engine plus electric generator)	2	- detection of leaks - ID of valves position - reading of local gauges					
		rotating equipment (pumps, chilllers,…)	2	- detection of leaks - reading of local gauges			Detection of over-heated zones	Detection of over-heated zones	detection of vibrations caused by misalignment or damaged bearings
	BELOW WATER								
	Foundation s	concrete based (GBF)	4	*External degradation/ cracking					
		steel structure (monopile, transition piece, jacket)	4	*External corrosion, *Structural damage, *External degradation/ cracking					
		Bolting	3	*External corrosion, *Structural damage, *External degradation/ cracking					
		scour protection material	3	*External corrosion, *Structural damage, *External degradation/ cracking					
	Floating hull	concrete based structure (e.g., windcrete concrete spar buoy, BW Ideol concrete barge floater)	4	*External degradation/ cracking					
		Steel structure (e.g., monopile, tension-leg platform (TLP), spar buoy)	4	*External corrosion, *Structural damage, *External degradation/ cracking					
	Corrosion Protection (CP) System	Anodes	2	*External corrosion *External degradation/ cracking					
	Mooring	polyester	4	*Structural damage, *External degradation					
		ultra-high molecular-weight polyethylene (e.g. Dyneema)	4	*Structural damage, *External degradation					
		chain	4	*External corrosion *Structural damage,					

				*External degradation/ cracking / pitting					
		Anchor piles	4	Usually not visually inspectable *External corrosion *Structural damage, *External degradation/ cracking					
	Electrical Cable system	Hangoff assembly	3	*External corrosion *Structural damage, *External degradation/ cracking					
		End connection	3	*External corrosion *Structural damage, *External degradation/ cracking					
		bend stiffener/restrictor	2	*External corrosion *Structural damage, *External degradation/ cracking					
		Subsea cable - Array	3					Overheating	
		Subsea cable - Export	3					Overheating	
		Ancillary - Strakes, clamps, buoys	2						
		Cable protection system on seabed	2						
	Offshore substation substructure	Jacket structure	4	External corrosion Structural damage, External degradation/ cracking					
		Anodes	2	Missing anodes					
		ICCP electrodes	2						
		HJ-Tubes	3						
		scour protection	3						
		Boat Landing	2	External corrosion Structural damage, External degradation/ cracking					

Register 3(b)-2: Columns 1,2,10-17

	1	2	10	11	12	13	14	15	16	17
	System	**Critical components**	**Acoustic**	**Microwave**	**Fiber optics**	**Fiber optics - Optical**	**Fiber optics - Thermal**	**Strain gauges**	**Digital twin / online monitoring**	**Coupon inspection**
	ABOVE WATER LINE									
ROTOR NACELLE	Rotor blades	Skin (external). Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip	Has been tried, not technically ready		Possible, not technically ready	Possible, not technically ready			Rain is a primary cause of leading edge erosion, monitoring of rainfall using DT might inform inspection intervals	

		Skin (internal) Note blade skin refers to all layers of the composite laminate, and thickness decreases from blade root to tip	Has been tried, not technically ready		Possible, not technically ready	Possible, not technically ready		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation (DT) models may be useful to inform inspection intervals	
		Spar. Structural element (beam or beams) internal to the rotor blade, often made of epoxy-resin infused layers of carbon fiber for high strength and low weight	Has been tried, not technically ready		Possible, not technically ready	Possible, not technically ready		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation (DT) models may be useful to inform inspection intervals	
		Bolts (blade root)	Ping tests with an automatic system? Frequency analysis		Instrumentation of critical bolts with strain sensitive fiber may allow detection of bolt tension loss			Life expectancy of common metal foil strain gauges is short	Potential high load events modeled via DT might inform the need for a bolt check	
	Rotor hub	Cast iron body	Possibly but would require a lot of R&D		Instrumentation of critical locations with strain sensitive fiber may allow detection of unexpected decrease or increase in strain	Instrument of critical locations may allow anomaly detection		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation models (DT) may be useful to inform inspection intervals	
	Main bearing	Races and rollers	Possibly but would require a lot of R&D						Potential high load events and fatigue damage estimation via DT might inform inspection interval.	
		Cast iron housing	Possibly but would require a lot of R&D		Instrumentation of critical locations with strain sensitive fiber may allow detection of unexpected decrease or increase in strain	Instrumentation of critical locations may allow anomaly detection		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation models (DT) may be useful to inform inspection intervals	
	Mainshaft/ Kingpin	Forged or cast body	Possibly but would require a lot of R&D		Instrumentation of critical locations with strain sensitive fiber may allow detection of unexpected decrease or increase in strain	Instrument of critical locations may allow anomaly detection		Life expectancy of common metal foil strain gauges is short	Potential high load events and fatigue damage estimation via DT might inform inspection interval.	
	Generator	Direct-Drive windings and magnets							Temperature history modeled by DT might inform potential failures	
		Direct-Drive rotor and stator housings carry high torque loads								

		Medium-speed windings and magnets							Temperature history modeled by DT might inform potential failures	
		Bearings	Possibly			Possibly				
	Gearbox (not relevant for direct-drive WTGs)	Gears	Possibly			Possibly				
		Bearings	Possibly			Possibly				
	Generator frame	Main weldment or casting	Possibly but would require a lot of R&D		Instrumentation of critical locations with strain sensitive fiber may allow detection of unexpected decrease or increase in strain	Instrument of critical locations may allow anomaly detection		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation models may be useful to inform inspection intervals	
	Bedplate	Cast iron body	Possibly but would require a lot of R&D		Instrumentation of critical locations with strain sensitive fiber may allow detection of unexpected decrease or increase in strain	Instrument of critical locations may allow anomaly detection		Life expectancy of common metal foil strain gauges is short	Once damage is detected, propagation models may be useful to inform inspection intervals	
	Yaw Drive	Yaw motors gearboxes, pinion, bearings, slew rings								
	Power Electronics	Electrical components							Temperature history might inform potential failures	
TOWER ASSEMBLY	Tower	Steel	Possibly but would require a lot of R&D		Instrument critical welds to detect unexpected changes in strain level	Instrumenting critical locations may allow anomaly detection		Measures strain (load) directly, but life expectancy of common metal foil strain gauges is short	Potential high load events and fatigue damage estimation via DT may be used to inform inspection intervals	
		Concrete	Possibly but would require a lot of R&D		Instrument critical locations to detect unexpected changes in strain level	Instrumenting critical locations may allow anomaly detection		Measures strain (load) directly, but life expectancy of common metal foil strain gauges is short	Potential high load events and fatigue damage estimation via DT may be used to inform inspection intervals	
		Hybrid (steel + concrete)	Possibly but would require a lot of R&D		Instrument critical welds to detect unexpected changes in strain level	Instrumenting critical locations may allow anomaly detection		Measures strain (load) directly, but life expectancy of common metal foil strain gauges is short	Potential high load events and fatigue damage estimation via DT may be used to inform inspection intervals	
		Bolts (tower top, mid, and base flanges)			Instrumenting critical bolts with strain-sensitive fiber may allow detection of bolt tension loss (future)					
OFFS		External coating								
		Internal coating								

	Offshore Substation Platform	Above water structure						- Monitoring of fatigue cycles - Detection of abnormal constraints	DT used to assess actual fatigue loading	Direct measurement of actual corrosion effect, but coupon must be retrieved
		Boat landing								
		Cranes								
		Transformer	- Detection of ultrasounds generated by Partial discharges - Detection of abnormal vibrations							
		HV GIS	- Detection of ultrasounds generated by Partial discharges - Detection of abnormal vibrations							
		HV cables and connectors	- Detection of ultrasounds generated by Partial discharges - Detection of abnormal vibrations							
		LV electrical cabinets								
		piping								
		valves								
		Emergency generators (combination of diesel engine plus electric generator)								
		rotating equipment (pumps, chilllers,…)	detection of bearing damages by ultrasound							
	BELOW WATER									
	Foundation s	concrete based (GBF)								Direct measurement of degradation due to corrosion, but coupon must be retrieved
		steel structure (monopile, transition piece, jacket)							fatigue overloading	Direct measurement of degradation due to corrosion, but

										coupon must be retrieved
		Bolting								Direct measurement of degradation due to corrosion, but coupon must be retrieved
		scour protection material								Direct measurement of degradation due to corrosion, but coupon must be retrieved
	Floating hull	concrete based structure (e.g., windcrete concrete spar buoy, BW Ideol concrete barge floater)								Direct measurement of degradation due to corrosion, but coupon must be retrieved
		Steel structure (e.g., monopile, tension-leg platform (TLP), spar buoy)								Direct measurement of degradation due to corrosion, but coupon must be retrieved
	Corrosion Protection (CP) System	Anodes								
	Mooring	polyester								ageing degradation
		ultra-high molecular-weight polyethylene (e.g. Dyneema)								ageing degradation
		chain								corrosion degradation
		Anchor piles								corrosion degradation
	Electrical Cable system	Hangoff assembly								corrosion degradation
		End connection								corrosion degradation

		bend stiffener/restrictor								corrosion/ageing degradation
		Subsea cable - Array			Structural damage Overheating	Structural damage	Overheating			corrosion/ageing degradation
		Subsea cable - Export			Structural damage Overheating	Structural damage	Overheating			corrosion/ageing degradation
		Ancillary - Strakes, clamps, buoys								
		Cable protection system on seabed								
	Offshore substation substructure	Jacket structure								corrosion degradation
		Anodes								
		ICCP electrodes								
		HJ-Tubes								
		scour protection								
		Boat Landing								

Criticality Rating	**Definition**
1. Cosmetic	e.g., minor damage that does not impact operation; timing of repair non-critical
2. Functional	e.g. could stop turbine from operating. Could degrade performance
3. Major	e.g., loss of blade, gearbox failure, subsea cable failure
4. Structural	e.g., catastrophic, primary load path, loss of asset

Register 4: Register of **remote inspection programs**

Explanatory notes:

- Summary of various aspects of remote inspection programs, how they are implemented, and how they support BSEE's self-inspection requirements.
- Register has been split into TWO tables (for readability), where Register 4-1 includes Columns 1-7, and Register 4-2 includes Columns 1, 8-12. For unified table and complete workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 4-1: Columns 1-7

	1	2	3	4	5	6	7
No.	**Inspection type**	**Remote or Manned? Why?**	**Components inspected**	**Description of use**	**Examples of identifiable failure modes**	**Remote Inspection Successes and Economic Benefits**	**Remote Inspection Failures**
	ABOVE WATER LINE						
1	Periodic visual inspection of AWL external structural condition	Remote: Drone launched from vessel near turbine: limited drone battery life requires nearby deployment.	External portions of: nacelle, towers, platform, ancillary structures AWL, connections to transition piece	Determine the condition of external key features in the above water portions of the support structure	Anomalies 5 cm or larger due to: external corrosion, stress cracking or deformation, external contact damage	Cost and time savings: can inspect multiple structures per day instead of an inspector-day per WTG, decreases transit time, reduces time working at heights exposed to the elements, thereby averting safety risk	Human-directed drones can pose higher risk of accidental damage to the blades; less nimble response to unplanned needs; drones may miss details that manual inspection would catch
2	Periodic visual inspection of external condition of wind turbine blades	Remote: Drone launched from vessel near turbine: limited drone battery life requires nearby deployment	Blades - exterior	Determine the condition of the external portion of the wind turbine blades	Adhesive and inter-fiber fractures, damage to web-flange joints, cracks in the trailing edge of rotor blades, and faulty bonding in the blade root area	Cost and time savings: environmental windows are wider (fewer delays), avoids industrial climbers transit, averted safety risk. Replaces traditional inspection conducted by workers at height exposed to the elements.	Less nimble response to unplanned needs; drones may miss details that manual inspection would catch
3	Periodic internal blade inspection - visual	Manned + Remote: Onboard inspection system (robot or drone) (including inspector-guided robot or drone)	Blades - interior	Determine the condition of the internal portion of the blades. Some technologies enable assessment of aspects of the external portions of the blade from the inside.	Damage to the shear web, interior cracks, structural manufacturing damage, corrosion or erosion of the bonding material.	Cost and time savings: partially avoids work and transit time for inspectors to walk the length of each blade, averting safety risk and reducing time working in confined spaces; potential to carry multiple tests in one pass, such as ultrasound, thermography, shearography, visual inspection or radiography.	Less nimble response to unplanned needs; drones may miss details that manual inspection would catch
	BELOW WATER LINE						
4	Periodic inspection of BWL external structural condition	Remote: ROV launched from a special purpose vessel within the wind farm	External portions of: foundations (fixed or floating) at and below the water line and above the sea bed, including the transition piece or platform connecting to the tower	Determine the condition of external key points in the subsea structure above the sea bed	Corrosion, stress, external contact; Millimeter-scale anomalies using modeling technology	Averted time for diver transit and diver limited subsurface duration; access to diver-limited depths; may also use sonar in addition to visible light; equipment can also clean marine growth, eliminating need for separate cleaning; can also conduct some repair tasks	Many ROVs are limited to low-current, high visibility waters; ROVs are not effective in the wave splash zone; ROVs can be more expensive on a per-day basis (but less expensive on a programmatic basis); large crewed vessel required for ROV transport and launch

5	Periodic inspection of BWL internal structural condition	Manned and remote: Combination of divers, technicians, and external or internal UV automated equipment can be used to determine thickness	monopile interior; spar buoy interior; transition piece interior; interior of other steel structure subject to corrosion	Determine degree of corrosion, whether uniform or from pitting; evaluate corrosion fatigue	Corrosion, corrosion pitting, corrosion fatigue	Combination of manned + use of automated equipment to inspect, and instrumentation to monitor interior steel structures for corrosion optimizes cost. Monitoring should be planned into the design, e.g. coupons (must be retrieved), galvanic anodes (remote monitoring), and/or strain gauges (remote monitoring).	Failure to inspect or monitor interiors of steel structures can lead to corrosion fatigue failure
6	Determine subsea export cable location	Remote: ROV launched from a special purpose vessel within the wind farm	Subsea cables	Determine the location of the export cable, including burial depth	Movement of the subsea cable laterally or progressive de-burial of the cable	Cost and time savings compared to traditional inspection method of a vessel towing submerged equipment; less intrusive on other waterway users (e.g., fishing)	Less nimble response to unplanned needs
7	Periodic visual inspection of mooring lines and anchors for floating wind foundations	Remote: ROV launched from a special purpose vessel within the wind farm	Floating wind mooring lines and anchors	Determine the integrity of the mooring lines and umbilical system, as well as anchors; assess marine growth	External corrosion, stress, external contact, and excessive marine growth on the top chains, clump weights, connections, spring buoys, bottom chains, and anchors	Cost and time savings compared to traditional inspection method of a vessel towing submerged equipment; less intrusive on other waterway users (e.g., fishing). ROV with video camera may catch defects that a diver might miss.	ROV with video camera may fail to capture defects that a diver would catch

Register 4-2: Columns 1,8-12

	1	8	9	10	11	12	13
		How does remote inspection support/enhance compliance with 30 CFR 585.824 - How must I conduct self-inspections?					
		(a) Develop a self-inspection plan specifying:		**(b) Report annually to BOEM, by Nov 1:**			
No.	**Inspection type**	**1) Type, extent, frequency of in-situ inspections of all mooring systems and floating facilities**	**2) How corrosion protection is monitored for AWL and BWL structures**	**1) List of facilities inspected in preceding 12 months**	**2) Type of inspection**	**3) summary of the inspection indicating what repairs, if any were needed, and overall structural condition of the facility.**	**Extent of application in offshore wind industry**
	ABOVE WATER LINE	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	
1	Periodic visual inspection of AWL external structural condition	Yes, drone inspections of external structures can be included in inspection plan - Assumed Annual	Yes. Coupons (must be retrieved to assess corrosion); galvanic probes (remotely monitored); strain gauges (remotely monitored) can be used to monitor corrosion in external AWL structures	Yes, reported annually. External portions of: nacelle, towers, platform, ancillary structures AWL, connections to transition piece.	Yes. The annual report can specify visual inspection, via drone.	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	Increasing adoption
2	Periodic visual inspection of external condition of wind turbine blades	Yes, drone inspections of blade exterior can be included in inspection plan - Assumed Annual	Yes. Anti-corrosion coatings on the rotor blade exteriors can be inspected annually using thermographic	Yes, reported annually. Blade exterior.	Yes. The annual report can specify visual inspection, via drone, as well as UT inspection, via crawler	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	Mainstream adoption

		inspection of blade exterior, visual, UT, and thermographic inspection to assess corrosion from UV radiation	inspection to check for UV corrosion.				
3	Periodic internal blade inspection - visual	Yes, drone or robot/crawler inspections of blade interior can be included in inspection plan - Assumed Annual	Yes. Cathodic protection system can help prevent integrity issues. First, a baseline CP survey should be performed to confirm fitness for service.	Yes, reported annually. Blade interior.	Visual, via drone or crawler robot (including inspector-guided drone or robot	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	Increasing adoption
	BELOW WATER LINE	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	**Does this comply/facilitate?**	
4	Periodic inspection of BWL external structural condition	Yes. Annual ROV inspections of BWL external structural structures can be included in the self-inspection plan	Yes. Advanced impressed current cathodic protection (ICCP) uses ICCP anodes and sensors to work together to both mitigate and monitor corrosion	Yes, reported annually. External portions of: foundations (fixed or floating) at and below the water line and above the sea bed, including the transition piece or platform connecting to the tower	Visual, via ROV	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	Mainstream adoption
5	Periodic inspection of BWL internal structural condition	Yes. Annual inspection of interiors BWL components (e.g., monopile, transition piece) both visual (via diver and/or ROV) and UT (remote), to assess corrosion damage.	Yes. Coupons installed during manufacturing, galvanic anodes that allow remote monitoring, strain gauges that identify changes in stress concentrations, indicating erosion or corrosion	Yes, reported annually. Monopile interior; spar buoy interior; transition piece interior; interior of other steel structure subject to corrosion	Visual, manned; UT, automated; real-time monitoring	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	
6	Determine subsea export cable location	Yes. Annual visual inspection (via ROV) to establish that subsea cables have not shifted or been compromised can be included in self-inspection plan	Yes. Subsea cables generally have zinc-coated armoring, overlain by a further protecting extruded polymeric lay	Yes, reported annually. Subsea cables.	Visual, via ROV	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	Increasing adoption
7	Periodic visual inspection of mooring lines and anchors for floating wind foundations	Yes. Semi-annual visual inspections of mooring lines using ROV with video camera can be specified in self-inspection plan.	Yes. Mooring chain is protected by an anti-corrosion coating as well as sacrificial anodes. Corrosion can be monitored by examining the video from the regular ROV inspections.	Yes, reported semi-annually. Floating wind mooring lines and anchors.	Visual, via ROV	Yes. The annual report can document any needed repairs carried out on the structure in compliance with 30CFR585.824.	In use

Register 5: Register of **optimal remote inspection intervals** in conjunction with manned inspections

Explanatory notes:

- The critical components listed in column C are the same as those from Task 3, Column C.
- For each component, we have identified the extent of RIT activity (as informed by Task 3) and the residual manned activity remaining.
- The References in columns H and I link to the summaries in Task 6, for convenience.
- For table that includes links to descriptions of referenced standards, RPs, etc., and workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

	System	Critical Components	Recommended inspection interval (from Standards/RPs)	RIT activity	Manned activity	References: Standard (ST), Recommended Practice (RP), Service Specification (SE), Offshore Standard (OS)	
	ABOVE WATER LINE						
1	Rotor blades	Skin (external)	regular inspection intervals as specified by the OEM (typically annual)	* Drone flies in pattern along blade exterior, covering the entire blade length, inspects structural integrity of laminates, adhesive joints at leading and trailing edges; * Drone records video of all surfaces plus high resolution still photos of areas of interest.	* Operator required to fly drone. * Operator is located on a vessel near the turbine. * Activity eliminated: - crew transfer from CTV to WTG platform - tower climb - crew rappelling down the length of the blade	DNV-ST-0376	
2		Skin (internal)	regular inspection intervals as specified by the OEM (typically annual)	* Drone flies or crawler moves in pattern along blade interior, covering entire blade length, inspects structural integrity of laminates, adhesive joints inside the blade (e.g., shear web), attached items (lightning protection), corrosion; * Drone records video of all surfaces plus high-resolution still photos of areas of interest	* Operator required to fly drone or crawler. * * Operator transfers from CTV to the WTG, climbs the tower to the nacelle, and enters the hub. * Operator is located in the rotor hub or blade root when flying the drone. * Activity eliminated: - Confined space entry of inspector into blade from hub (reduction of one person as blade entry attendant not needed) - Inspector walking/crawling the length of the blade interior to conduct visual inspection	DNV-ST-0376	
3		Spar (internal)					

4		Bolts (blade root)	regular inspection intervals as specified by the OEM (typically annual)	* Drone with camera records HD video of bolt markings to check for slippage; part of the internal blade drone inspection campaign	* Manual spot-check bolt pre-tension for bolt loosening * Activity eliminated: - Time saved by technician not having to check markings on each bolt	DNV-ST-0376	DNV-ST-0361
5	Rotor hub	Cast iron body	At least once every 5 years	* None.	* Manual visual inspection as specified by OEM.	DNV-SE-0190	
6	Main bearing	Races and rollers	As per OEM recommendation, accounts for CMS	* CMS monitors the main bearings. Sensors include: temperature, acoustic, vibration analysis, wear debris analysis	* Manual inspection of the main bearing required; includes looking for wear, checking for smooth operation (no 'play' in the bearing) * Activities eliminated: - Time saved by relying on CMS system to indicate when inspection is required. * Reduced time per technician inspection	DNV-SE-0439	
7		Cast iron housing	as needed (no regular inspection)	* Visual inspection using drone with camera detecting external corrosion	* Manual visual inspection - close inspection. * Activity eliminated: - Time saved not having to conduct general inspection of corrosion	DNV-ST-0376	
8	Mainshaft / Kingpin	Forged or cast body	At least once every 5 years	* None.	* Manual visual inspection as specified by OEM.	DNV-SE-0190	
9	Generator	Direct-Drive windings and magnets	As per OEM recommendation, accounts for CMS	* CMS monitors the generator. Sensors used include: temperature, acoustic, electrical effects monitoring, power generation.	* Manual inspection per OEM maintenance and inspection plan * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-SE-0439	
10		Direct-Drive rotor and stator housings carry high torque loads					
11		Medium-speed windings and magnets					
12		Bearings					
13	Gearbox	Gears	As per OEM recommendation, accounts for CMS	* CMS monitors the gearbox/drive train. Sensors used include: temperature, acoustic.	* Manual inspection per OEM maintenance and inspection plan * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-SE-0439	
14		Bearings					
15	Generator frame	Main weldment or casting	At least once every 5 years	* None.	* Manual visual inspection as specified by OEM.	DNV-SE-0190	
16	Bedplate	Cast iron body	At least once every 5 years	* None.	* Manual visual inspection as specified by OEM.	DNV-SE-0190	
17	Yaw Drive	Yaw motors, gearboxes, pinion, bearings, slewrings	As per OEM recommendation, typically annual	* None.	* Manual inspection per OEM maintenance and inspection plan	DNV-ST-0361	
18	Power Electronics	Electrical components	As per OEM recommendation, typically annual	* CMS (temperature, electrical effects monitoring, power generation).	* Manual inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0076	

19	Tower	Steel	Interval is based on magnitude of SF in the design (typically annual)	* Drone equipped with camera conducts visual inspection of steel tower including fatigue cracks, dents, deformations, bolt markings, corrosion protection systems, anchor points for fall protection, lifting appliances. * Crawler with UT or other NDT inspects steel structures for fatigue cracks, corrosion	* Activity eliminated: - Technician rappelling down tower - Tower climb	DNV-ST-0126	
20			Corrosion control requires in-service inspection (typically annual)	* Drone with camera visually inspects exterior coating degradation * Crawler with UT sensor measured wall thickness to detect corrosion	* Drone is operated manually from a nearby vessel * Crawler operated manually from tower base platform * Activity eliminated: - crew transfer from boat to WTG - Tower climb - Interior tower climb	DNV-RP-0416	
21		Concrete	Interval should not exceed one year	* Drone inspection of concrete tower includes video of concrete surfaces (cracks, abrasion, spalling and any signs of corrosion of the steel reinforcement and embedments), concrete structures, anchor bolt connections (regular visual inspections), post-tensioning systems	* Drone is operated manually from a nearby vessel * Manual inspection of concrete tower includes anchor bolt pre-tension connections (**close** visual inspections) * Activity eliminated: - Crew time saved from not having to do general visual inspection - Technician rappelling down tower	DNV-ST-0126	
22		Hybrid (steel + concrete)	Interval should not exceed one year	* See steel and concrete (above)	* See steel and concrete (above)	DNV-RP-0416	DNV-ST-0126
23		Bolts (tower top, mid, and base flanges)	Interval should not exceed one year	* Drone with camera flies around interior perimeter of the tower base, mid, and top flanges to record bolt markings,	* Technician conducts bolt pre-tension checks * Technician conducts detailed inspection of cracks (NDT) near bolts * Activity eliminated: - Time saved not having to conduct general inspection of bolt markings	DNV-ST-0361	
24	Offshore Substation Platform	External coating	Annual (visual and thickness test)	* Visual inspection using UAS and crawler -automatic mapping of defects	* Manually conduct detailed, close inspection of identified defects * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
25		Internal coating	Every 5 years	* Visual inspection with crawler - automatic mapping of defect	* Manually conduct detailed, close inspection of identified defects * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
26		Above water structure	Annual	* UAS: detection of indents, corrosion and deformation * Crawler: detection of cracks on structure not safely accessible * Structural health monitoring system: detection of abnormal movements	* Manually conduct bolt pretention check and detailed (close) analysis of cracks (NDT) * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
27		Boat landing	Annual	* UAS: detection of indents, corrosion and deformation * Crawler: detection of cracks on structure not safely accessible	* Manually conduct bolt pretention check and detailed (close) analysis of cracks (NDT) * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
28		Cranes	As per OEM recommendation (typically annual)	* UAS or crawler: Visual identification of cracks, indents, deformation, paint damage, detection of oil leak	* Manually conduct close visual inspection of identified anomalies * Manually conduct functional test, safety features test, load tests * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	

				* Crawler: visual check of oil levels in the technical compartment			
29		Transformer	As per OEM recommendation	* Crawler robot: detection of over-heated components, Detection of ultrasounds generated by partial discharges, detection of abnormal vibrations * CMS monitoring: dissolved gases, partial discharges, short circuit, temperature, gas bubbling	* Manually inspect inside electrical cabinets or other elements that need to be dismantled. * Manually conduct oil sampling * Activity eliminated: - Overall inspection time saved - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	
30		HV GIS	As per OEM recommendation	* Crawler robot: detection of over-heated components, Detection of ultrasounds generated by Partial discharges, detection of abnormal vibrations * CMS monitoring: partial discharges, temperature, short circuit, SF6 leak	* Inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Overall inspection time saved - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	
31		HV cables and connectors	As per OEM recommendation	* Crawler robot: visual inspection of cable and fasteners, detection of over-heated areas.	* Inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
32		LV electrical cabinets	As per OEM recommendation	* Crawler robot: detection of over-heated components, Detection of ultrasounds generated by Partial discharges, detection of abnormal vibrations * CMS monitoring: partial discharges, temperature, short circuit, SF6 leak	* Inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Overall inspection time saved - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	
33		piping	Depends on system criticality	* Crawler robot: Visual identification of cracks, indents, deformations, detection of leaks.	* Manual visual inspection required of areas not accessible by crawler. * Pressure testing when necessary * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
34		valves	Depends on system criticality	* Crawler robot: Visual identification of cracks, indents, deformations, detection of leaks, identification of valves position	* Manual actuation of valves if necessary * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
35		safety systems	As per OEM recommendation and applicable regulation (typically yearly)	* Drone with camera for visual inspection	* Maintenance and test of safety systems (fire fighting, etc.…) * Re-certification of safety systems and portable extinguishers * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
36		Emergency generators (diesel)	As per OEM recommendation (typically 3-monthly)	* Remote start test from SCADA system * Remote monitoring of oil levels, battery charge, etc.…	* Manual inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	
37		Helideck	As per OEM recommendation	* UAS or crawler: monitor helideck's surface condition (free from oil, grease, snow, guano...)	* Manual test of the safety systems * Manual inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	
38		rotating equipment (pumps, chillers,…)	As per OEM recommendation	* Crawler robot or CMS monitoring: detection of over-heated components, Detection of ultrasounds generated by defects, detection of abnormal vibrations	* Manual test of the safety systems, and functional tests * Manual inspection requiring opening of cabinets or dismantling of elements. * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0145	

	BELOW WATER LINE						
39	Foundations	concrete based (GBF)	Risk-based inspection (RBI). * Typical Interval should not exceed one year	* ROV inspection of concrete hull includes video of concrete surfaces (cracks, abrasion, spalling and any signs of corrosion of the steel reinforcement and embedments), concrete structures, anchor bolt connections (regular visual inspections), post-tensioning systems	Manual inspection of concrete hull includes **close** visual inspections and looseness checks * Activity eliminated: - Divers	DNV-ST-0126	
40		steel structure (monopile, transition piece, jacket)	Risk-based inspection (RBI). * Corrosion control requires in-service inspection (typically annual for exterior, for monopile every 5 years)	AWL: * Drone inspects exterior coating degradation via visual examination using a camera * Crawler with UT sensor detects wall thickness * Crawler robot (e.g. iFrog) cleans/inspects Interior monopile up to 60 m BWL BWL (exterior): * ROV with camera conducts visual inspection * Crawler robot with UT sensor detects corrosion	* Diver conducts close inspection of exterior * Diver not needed for interior MP inspection, improving safety * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0126	
41		Bolting	Annual	AWL: Drone with camera inspects transition piece to tower bolting. BWL: * Mini-ROV or submersible drone visually inspects pile/foundation to transition piece connection bolting	* Manually conduct bolt pretention check and detailed (close) analysis of cracks (NDT) * Activity eliminated: - Overall inspection time saved	DNV-ST-0126	
42		scour protection material	Depends on seabed conditions	* ROV with camera monitors shifting of scour material * ROV with tool attachments restores scour protection to proper location	None.	DNV-ST-0126	DNV-SE-0190
43	Floating hull	concrete based structure (e.g., windcrete concrete spar buoy, BW Ideol concrete barge floater)	Risk-based inspection (RBI): * Interval based on assessment of failure risk * Typical Interval should not exceed one year Offshore Class Surveys: * Surveys required to maintain Class include annual, intermediate (2.5 yrs), and major (every 5 years)	* ROV with camera conducts visual inspection of concrete hull: - surfaces (cracks, abrasion, spalling and any signs of corrosion of the steel reinforcement and embedments), - concrete structures, - anchor bolt connections (regular visual inspections), - post-tensioning systems	* Scope for manual inspection of concrete hull includes **close** visual inspections and looseness checks * Activity eliminated: - Fewer inspection visits required and/or less time needed per visit	DNV-ST-0119	DNV-RU-OU-0512
44		Steel structure (e.g., monopile, tension-leg platform (TLP), spar buoy)	Risk-based inspection (RBI). * Corrosion control requires in-service inspection (typically annual)	* Drone with camera conducts visual inspection of exterior coating degradation (corrosion)	* Drone is operated manually from floating hull or nearby vessel * Crawler operated manually from floating hull * Activity eliminated: - Potentially no crew transfer from CTV to the WTG platform - Overall inspection time saved	DNV-ST-0119	

45	Corrosion Protection (CP) System	Anodes	As per OEM recommendation, typically annual	* Visual inspection by ROV-operated cameras * Also, on-line recording of the protection potential and anode current output has been developed	* Close visual inspection by diver * Activity eliminated: - Overall inspection time saved	DNV-RP-0416	DNV-RP-B401
46	Mooring	polyester	As per OEM recommendation	* Drone with camera conducts visual inspection of chain/ropes above and in the splash zone. * ROV/UAV with camera inspects chain/ropes below approximately 15 m water depth	* In less than 15m water depth, diver (or mini-ROV) is required. * Underwater drone/ROV/AUV can't operate in depths less than 15m. * Activity eliminated: - Overall inspection time saved.	DNV-RP-E308	API RP 2MIM
47		ultra-high molecular-weight polyethylene (e.g. Dyneema)					
48		chain					
49		Anchor piles	Depends on seabed conditions	* ROV with camera conducts visual inspection of exposed parts (above seabed); water depth must exceed 15 m for ROV to operate.	* In less than 15m water depth, diver (or mini-ROV) is required. * Underwater drone/ROV/AUV can't operate in depths less than 15m. * Activity eliminated: - Overall inspection time saved.	DNV-RP-E308	API RP 2I
50	Electrical Cable system	Hangoff assembly	regular inspection intervals as specified by the OEM (typically annual)	* Drone with camera visually inspects cable above and in the splash zone. * Mini-ROV with camera can inspect in water depths ranging from 0-30m * ROV/UAV with camera visually inspects cable and cable protection system exceeding 15 m water depth.	* In less than 15m water depth, diver (or mini-ROV) is required. * Underwater drone/ROV/AUV can't operate in depths less than 15m. * Activity eliminated: - Overall inspection time saved.	DNV-ST-0359	
51		End connection					
52		bend stiffener/restrictor					
53		Subsea cable - Array					
54		Subsea cable - Export					
55		Ancillary - Strakes, clamps, buoys					
56		Cable protection system on seabed					
57	Offshore substation substructure	Jacket structure (Steel)	Risk-based inspection (RBI). * Corrosion control requires in-service inspection (typically annual)	AWL: * Exterior coating degradation is apparent by visual examination via drone * Wall thickness detected via UT sensor mounted on a crawler (exterior) BWL: * ROV with camera for visual inspection	AWL: * Drone is operated manually from nearby vessel * Crawler operated manually from substructure BWL: * ROV operated manually from vessel * Crawler operated manually from substructure	DNV-ST-0145	DNV-ST-0126

				* Crawler with UT sensor (exterior)			
58		Anodes (Corrosion protection)	As per OEM recommendation, typically annual	* Visual inspection by ROV-operated cameras * Also, on-line recording of the protection potential and anode current output has been developed	* Close visual inspection by diver * Activity eliminated: - Overall inspection time saved	DNV-RP-0416	DNV-RP-B401
59		ICCP electrodes					
60		HJ-Tubes	Annual	UAS: detection of indents, corrosion and deformation Crawler: detection of cracks on structure not safely accessible	* Manually conduct bolt pretention check and detailed (close) analysis of cracks (NDT) * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	
61		scour protection	Depends on seabed conditions	ROVs, or vessel in water depths less than 15 m: *monitor shifting of scour material * restore scour protection to proper location	None.	DNV-ST-0126	DNV-SE-0190
62		Boat Landing	Annual	UAS: detection of indents, corrosion and deformation Crawler: detection of cracks on structure not safely accessible	* Manually conduct bolt pretention check and detailed (close) analysis of cracks (NDT) * Activity eliminated: - Overall inspection time saved	DNV-ST-0145	

Acronyms (For Tasks 5 and 6):	Definition
CMS	Condition Monitoring System
CP, GACP	Cathodic protection, Galvanic anode cathodic protection
NDT	Non-destructive testing
OEM	Original Equipment Manufacturer
ROV	Remotely Operated Vehicle
UAV	Underwater Autonomous Vehicle
UT	Ultrasonic sensor (detects corrosion)
WTG	Wind turbine generator (includes tower)

Register 6: Register of **current standards (ST), recommended practices (RP), service specifications (SE), offshore standards (OS), and rules for classification (RU)** that can be met by employing RITs

Explanatory notes:

- There exist many bodies of standards pertaining to wind turbines, offshore wind, offshore structures, floating structures, offshore substations, subsea electrical cables, etc.
- Exhaustively cataloguing all standards that can be met by RITs was outside the scope of this project.
- DNV has a comprehensive library of in-house documents that have been developed over decades pertaining to many aspects of offshore wind, both fixed and floating.
- DNV's standards, recommended practice, etc., reference relevant requirements, acceptable methods and useful guidance from other standards bodies such as API, CIGRE, EN, IEC, ISO among others.
- To complete Register 6, DNV has drawn primarily from our in-house documents as representative of the most current international standards, guidelines, etc. Several standards from the American Petroleum Institute (API) have been included as well.
- A table of acronyms is provided in Register 5
- For further details regarding the requirements or recommendations for each standard listed below, and complete workbook including all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.
- The complete DNV documents listed below can be found at the following website (subscription required): https://rules.dnv.com/servicedocuments/dnv/#!/

No.	Standard ID	Title	Subsection	Requirements or recommendations (Summary)	RIT	Describe how RIT meets this standard, guideline, or practice
	ABOVE WATER LINE					
1	DNV-RP-0175	Icing of wind turbines	Section 5	* Continuous monitoring of ambient temp, wind sensors, nacelle vibrations to detect icing * Drone w/video systems deployed as needed to inspect blades, hub, nacelle, and tower	CMS, Drone with camera	* CMS provides continuous data and real-time assessment of the system * Drone with camera can provide confirmation of icing incident and/or conditions for safe restart
2	DNV-RP-0363	Extreme temperature conditions for wind turbines	Section 5	* Inspection and maintenance to be performed based on assessment of potential failures detected electrically or through sensors	CMS, Drone with camera	CMS provides continuous data and real-time assessment of the system * Drone with camera can provide confirmation of icing incident and/or conditions for safe restart
3	DNV-RP-0416	Corrosion protection for wind turbines	Section 4, 6	* Includes visual inspection and maintenance of corrosion protection systems * Industry typical practice: - general visual corrosion inspection annually -	* Drone with camera, * Crawler robot with magnetic flux leakage detector	Can detect corrosion visually (using camera) as well as via NDT (e.g., magnetic flux leakage detector, or ultrasonic detection of material thickness compared to baseline)

4	DNV-RP-0585	Seismic design of wind power plants	Section 6	* Inspection of critical components should immediately follow earthquake events	CMS, Drone with camera, crawler with ultrasonic sensor	Combination of CMS checks (for any abnormal data) and drone with camera that can conduct "health checks" on specified wind power plant assets prior to returning to normal operation.
5	DNV-SE-0190	Project certification of wind power plants	Section 1, 2, 3, 4, 8	* Project Certification includes…periodic on-site inspections…during the in-service phase, examining substation topside, rotor-nacelle assembly of the WTG, support structures, scour protection, and power cables * Select number of installations should be inspected each year * All assets should be inspected at least once in 5-year period * More frequent inspections at the beginning and end of the project lifetime are recommended	Drone, crawler (for WTG and platform), 4-legged robot (for interior substation inspection), ROV, AUV, mini-ROV (for subsea structure and electrical cables)	Remote inspections via ROV, AUV, drone or crawler may be used for on-site visual inspections
6	DNV-SE-0439	Certification of condition monitoring	Section 4, 6	* CMS systems shall be used permanently on WTGs and accounted for in the maintenance and inspection plan * CMS monitors the drive train, tower, rotor blades, main gearbox oil, main bearings, and foundation	Condition Monitoring System (CMS)	A certified CMS meets this service specification.
7	DNV-ST-0126	Support structures for wind turbines	Section 9	* Inspection and maintenance to be performed based on assessment of potential failures * Specific inspection scope to be tailored according to steel or concrete structures * Interval between inspections for critical items should not exceed one year * Entire project should be inspected at least once in 5-year period * Periodic inspection of scour protection may be required * Subsequent inspection intervals to be set based on findings	AWL: * Drone with camera * crawler robot with camera, UT or magnetic flux leakage detector, or other NDT BWL: * ROV with camera	AWL: * Drone with camera for AWL inspection of bolts, welds, ancillary structure, surface coating crawler robot with camera, UT or magnetic flux leakage detector, or other NDT to detect fatigue cracks, weld cracks BWL: * ROV with camera for BWL inspection of fixed foundations (steel or concrete) and scour protection
8	DNV-ST-0145	Offshore Substations	Section 11	* Inspection and maintenance program shall be based on manufacturer's required frequency and historical data * RBI shall be based on the design life of the system * Interval between inspections for critical items should not exceed one year * Subsequent inspection intervals to be set based on findings	AWL: * Drone with camera * 4-legged robot with camera, UT or magnetic flux leakage detector, or other NDT BWL: * ROV with camera	AWL: * Drone with camera for AWL inspection of bolts, ancillary structure, surface coating * 4-legged robot with camera, UT or magnetic flux leakage detector, or other NDT to detect fatigue cracks, weld cracks BWL: * ROV with camera for BWL inspection of mooring lines, anchors
9	DNV-ST-0361	Machinery for wind turbines	Section 3, 5, 8, 11	* Requirement for inspection of bolted connections as a part of regular preventative maintenance * Corrosion protection to be ensured by combination of appropriate materials, coatings and inspections * Inspection regimen and intervals set according to criticality of components, safety considerations	CMS, Drone with camera	CMS provides continuous data and real-time assessment of the system * Drone with camera can inspect certain components as indicated by CMS assessment, but certain detailed inspection (e.g., bolt pre-tension) must be done manually

10	DNV-ST-0376	Rotor blades for wind turbines	Section 7	* Inspection and maintenance to be performed on regular basis * Interval based on OEM procedures if available, but no absolute normative requirement * Industry typical practice: - Exterior visual inspections annually - Internal visual inspections as-needed - Bolt torque checks during regular maintenance intervals	Drone with camera (exterior and interior), Crawler robot with camera and UT sensors (exterior and interior)	Can visually inspect blades, both exterior and interior, using a drone with video camera Can conduct UT inspection using a crawler with UT sensors
	DNV-ST-0076	Design of electrical installations for wind turbines	Section 5.3, 6.2, 10.3	*Each frequency converter shall be routinely tested and inspected after production. *The complete lightning protection system and earthing system shall visually inspection annually and have a full inspection at least every two years. *Inspection and maintenance on high-voltage switchgears must observe national and local regulations	Drone with camera (exterior and interior), Crawler robot with camera and UT sensors (exterior and interior)	Can visually inspect frequency convert and lightning protection system with camera drone Can conduct UT inspection using a crawler with UT sensors
	BELOW WATER					
11	30 CFR 250.919	In-service Inspection Requirements (BOEM)	250.919	* BOEM Inspection, Maintenance, and Assessment of Platforms * Comprehensive annual in-service inspection report - list of all platforms inspected in preceding 12 months - extent and type of inspections - summary of inspection results and needed repairs * List of any structures exposed to extreme conditions (e.g., hurricane), must submit summary report - Affected structures and inspection plan for each - Description of damage that may affect structural integrity	All RITs listed below	The RITs described below would fulfill, in whole or in part, the requirements in 30 CFR 250.919. * The standards and other documents listed below provide specific detail on how each component can be put to use for
12	DNV-ST-0119	Floating Wind Turbine Structures	Section 15	* Inspection and maintenance to be performed based on assessment of potential failures * Specific inspection scope to be tailored according to steel or concrete structures * Interval between inspections for critical items should not exceed one year * Entire project should be inspected at least once in 5-year period * Subsequent inspection intervals to be set based on findings	AWL: * Drone with camera, * Crawler with magnetic flux leakage detector, UT BWL: * ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	AWL: * Drone with camera can inspect for deformations, fatigue cracks * Crawler with magnetic flux leakage detector or UT sensor can detect steel thickness for corrosion BWL: * ROV, mini-ROV, AUV with cameras can inspect mooring system (steel or synthetic)
13	DNV-RU-OU-0512	Floating offshore wind turbine installations	Chapter 4, Section 1, 1.2, and Section 5	Preferred inspection requirements * Inspections carried out based on a risk-based inspection (RBI) program; assumes access to data analytics based on sensor data * Inspections carried out on a representative number of installations, at intervals determined based on RBI plan	AWL: * Drone with camera, * Crawler with magnetic flux leakage detector, UT BWL: * ROV, AUV (water depths greater than 15 m)	AWL: * Drone with camera can inspect for deformations, fatigue cracks * Crawler with magnetic flux leakage or UT detector can detect steel thickness for corrosion, BWL: * mini-ROV, AUV with cameras can inspect mooring system (steel or synthetic)

					* mini-ROV (water depths up to approx. 30 m)	
14	DNV-RP-E308	Mooring integrity management	Section 7.3.3	* Annual survey required, incl. documentation review and general visual inspection of visible parts of mooring system.	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m) * semi-autonomous crawlers	ROVs, mini-ROVs to conduct visual (with cleaning), sonar 3D depth scanning, or bathymetry surveys. Semi-autonomous crawlers to do detailed surveys of continuous sections of wire and fiber rope
15	DNV-OS-E303	Offshore Fibre Ropes	Table 8	* References API RP 2I for in-service inspection of mooring hardware for floating structures	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	Visual survey (inspection) of mooring lines and hardware in water depths exceeding approx. 15 m can be carried out using ROV or AUV
16	API RP 2SK	Design and Analysis of Stationkeeping Systems for Floating Structures	K.2.6	Refers to API RP 2I; components should be surveyed at least once in 5-year period	See API RP 2I	See API RP 2I
17	API RP 2MIM	Mooring Integrity Management	5.2.2	* Inspection process establishes a baseline fitness-for-service * Risk Based Inspection (RBI) is allowed * Data is gathered at inspection intervals informed by risk assessment	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	ROV or AUV with video camera can carry out RBI per the defined risk-based inspection plan in water depths greater than 15 m. Mini-ROVs can be used in depths ranging from 0 to 30 m.
18	API RP 2I	In-service Inspection of Mooring Hardware for Floating Structures	4.5.3	* Inspection interval varies based on project design * Minimum requirements for inspecting chains, steel, and fiber rope components include: - As-built survey carried out within three months after completion of initial hookup of the mooring system - Components should be surveyed at least once in 5-year period - Severe storms, lightning, collision etc. trigger an immediate Special Event survey	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	Visual survey (inspection) of mooring lines and hardware in water depths exceeding approx. 15 m can be carried out using ROV or AUV
19	API RP 2SM	Recommended Practice for Design Manufacture, Inspection, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring	10.1	* A plan for the fiber rope inspection, maintenance, and condition assessment shall be developed as per API 2I.	See API RP 2I	See API RP 2I
20	DNV-ST-0359	Subsea power cables for wind power plants	Section 6.3	* Continuous monitoring records status of system: electrical - voltage, current, power; thermal - temperature; and mechanical - tension, bending, vibration * Frequency of external inspections based on detailed external inspection plan, determined based on assessment of multiple factors * Critical sections of the cable system (site-specific) should be inspected at suitable intervals (typically annual).	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	ROV or AUV with video camera can carry out inspections per the external inspection plan in water depths greater than 15 m. Mini-ROVs can be used in depths ranging from 0 to 30 m.
21	DNV-RP-F401	Electrical power cables in subsea applications	Section 1.1	* DNV RP provides additional detail with regards to electrical power cables suspended in deep water when international standards do not give	* ROV, AUV (water depths greater than 15 m)	ROV or AUV with video camera can carry out inspections per the external inspection plan in water depths greater than 15 m. Mini-ROVs can be used in depths ranging from 0 to 30 m.

				requirements for such cables on a detailed level. * Cables are assumed to be designed and fabricated according to existing IEC standards.	* mini-ROV (water depths up to approx. 30 m)	
22	DNV-RP-B401	Cathodic Protection Design	Section 7	* Annual inspection is typically recommended - CP potentials of objects that are removed, and closed-circuit potentials of selected anodes - visual inspection by ROV operated cameras or divers	* ROV, AUV (water depths greater than 15 m) * mini-ROV (water depths up to approx. 30 m)	* ROV, AUV or mini-ROV can do visual inspection via camera, to partially meet the RP.
	DATA MANAGEMENT AND SECURITY					
	DNV-RU-OU-0512	Floating Offshore Wind Turbine Installations	Chapter 2.7.3, Chapter 4, Section 5, Part 4: Data and applications.	* All mooring lines shall be inspected in-water, during a 5 year period, using a combination of ROV and divers	All	
	DNV-RP-0497	Data Quality Assessment Framework	Sections 2.3, 2.4, 5.3,	*Data should be viewed as an asset, thus it should be governed by an asset management system, in order to gain value from the data. *Risk assessments to be performed at several levels of governance *Employees responsible for data management must be skilled and have defined responsibilities *Data quality processes should be implemented to measure and improve the quality of data management and data	Any RIT that collects data that can be processed and reviewed.	
	DNV-RP-0496	Cyber security resilience management for ships and mobile offshore units in operation	Sections 1, 2, 3, 4	*Cyber Security responsibilities should be clearly defines and shared by different roles *A thorough cyber security assessment will have a high level assessment, a focused assessment, and an in depth assessment *Technical solutions against cyber attacks include hardened firewalls, authentication concepts, network segregation, and secure software design and implementation *It is important to list all critical systems vulnerable to cyber attacks *Cyber security policies need to be audited and improved regularly. *Management reviews should be carried out at least one a year in order to follow-up the implementation and development of the cyber security management system	All	
	DNV-RP-A204	Qualification and assurance of digital twins	Sections 7.3, 7.5	*Data from external sources shall need to meet data quality requirements and should be enforced through service level agreements or be monitored to assess conformity to requirements	RITs that use 3D imaging, infrared camera, etc., to create a digital twin.	

				*There should be documented procedures and practices for adding, modifying, and voiding data *Authorized users should only have access to data relevant to their specific purpose *Revision history of data should be maintained. Modifications should documented and annotated. *Data management maturity assessments should be conducted to ensure good quality data. Results of the assessment should be documented and may prescribe mitigating actions with implementation timelines if improvement is necessary. *Data quality assessments should be conducted every two years to ensure requirements are still relevant *A cyber security management plan should establish, implement, and operate practices to achieve proper cyber security		
	DNV-RP-0317	Assurance of sensor systems	Sections 5.3, 5.6	*Good data management procedures should be implemented so that data assets are formally managed and can achieve governance goals *Data management roles are typically organized into different roles that have their own responsibilities	RITS that use sensors	
	DNV-RU-OU-0300	Fleet in Service	Sections 4.3, 4.12	*Owners should be in knowledgeable in data management and be able to achieve proper data quality *A program should be in place that goes over the data integrity process in detail and how it will be executed over the service life	RITs that are on or below water	
	DNV-RP-0575	Cyber security for power grid protection devices.	Section 4	*The asset owner should be the one to implement a cyber security management plan *All employees should be made aware of cyber security protocols. Combined testing with training repeated 2-3 times a year results in measurable cyber security awareness *The level of cyber security maturity should be assessed regularly *Cyber security measures should be included in proposals and contracts with vendors *Hardening measures include blocking unused ports and protocols, removing unused applications and services, disabling interfaces for portable media, disabling not required wireless interfaces, blocking/protection of physical and logical access to diagnostics and configuration ports, disabling default accounts, restricting or denying access to shared folders, changing default passwords, setting password restrictions, idle timeout, etc., disabling temporary vendor access established during commissioning.	RITs associated with offshore substations	

				*Updates from software and operational systems should gave security fixes and updates installed as soon as possible. *Procedures should be put in place for actions to take if a cyber security breach were to occur.		
	DNV-RU-SHIP Pt.6 Ch. 5	Equipment and design features	Section 21	*There can be several levels of cyber security depending on the vulnerability of an asset *Each system and asset should be documented, including their cyber security capabilities, diagnostics, and alarming functionalities *Transfer of data between secure zones to/from removable devices should be managed to control the exchange of information *Compliance to the cyber security management plan should be audited regularly.		
	DNV-ST-0322	Management systems for auto-remote operations	Section 3.5	*The cyber security planning, implementation, and operation should be documented		
	DV-OS-D203	Integrated Software dependent systems (ISDS)	Sections 1.2	*Data within Integrated Software dependent systems need to have cyber security policies that are defined and communicated to vendors		

Register 7: Register of remote systems that can **perform maintenance, testing, repairs and/or component replacements**

Explanatory Note:

This register presents the capabilities of remote technologies to perform tasks OTHER than visual inspection.

List of Acronyms can be found at the bottom of the table.

Register has been split into TWO tables (for readability), where Register 7-1 includes Columns 1-10, and Register 7-2 includes Columns 1, 11-19. For unified table and complete workbook with all registers, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 7-1: Columns 1-10

	1	2	3	4	5	6	7	8	9	10
#	**Manufacturer/ Service Provider or Operator**	**Equipment/ Service name**	**Remote Technology Type**	**Is the equipment in commercial use or under development?**	**Number of years in commer cial use**	**If commercial, project references**	**Technical Specifications**	**Payload tools**	**Deployment method and additional equipment required**	**Affected offshore wind structures**
ABOVE WATER										
	MANUFACTURERS									
1	Superdroid robots	HD2	caterpillar robot with robotic arm	Commercial	3		Total Width: ~20", Total Length: ~38" Height (Parked): ~26".6-Axis Arm. Shoulder rotation: 180 degrees. Elbow rotation: 270 degrees. Wrist rotation: Continuous Parallel Finger Gripper: 4.5" opening with 65lb squeeze force	5-Axis removable arm High intensity LED lights Gripper and rear IR camera with 30x zoom	Deployed from rotor hub	Blade interior
2	Bladebug	crawler robot	crawler robot with camera, UT sensor	Commercial	2		6 independent legs that use suction to maintain connection to the blade surface	camera, UT NDT	Deployed from nacelle	Blade exterior
3	Rope Robotics	BR8 Robot	Robot hoisted to blade using ropes	Commercial	1	Partnered with major Danish developer, 2021		HD camera, laser scanner, robot arm w/repair capabilities	Ropes deployed from the nacelle lift robot from base platform	blade surface, esp. leading edge
4	EddyFi	Magg crawler robot	Small, tethered robot equipped with rare-earth magnets that attaches to steel towers	Commercial	<4		Crawler width 310mm (12.2in) or 480mm (18.9in), Vehicle weight 6.2kg (14lb) or 36kg (80lb), Depth rating 60m (200ft), Maximum tether length 100m (330ft) or 1000m (3300ft)	360-deg HD video/still camera, laser-guided, ACFM (alternating current field measurement), ECA (Eddy current array testing), NDT	Deployed from tower base and robot climbs up tower for external inspections of tower or blade, or deployed from inside the blade hub for internal	Blade (exterior and interior), tower

								toolbox, and UT testing gear	blade and spar inspection	
5	Skygauge Robotics	The SkyGuage	Drone with UT sensor	Commercial	<1		Skygauge Robotics' drone is equipped with a 4k 30 fps camera, a Olympus 38DL PLUS ultrasonic thickness gauge, and a dual transducer to measure the thickness of paint and the metal behind it.	UT sensor, HD camera	Deployed from CTV/SOV	blade, tower, OSS
6	Skyline Drones		Drone with UT sensor	Commercial				UT sensor	Deployed from CTV/SOV	blade, tower, OSS
	SERVICE PROVIDERS									
7	SkySpecs	Operations & Asset Management	Drones with thermal imaging capability	Commercial				HD and Thermal camera (IR)	Deployed from CTV/SOV	Blade exterior
8	Precision hawk	Drone Pilot Network	Drones with thermal imaging capability	Commercial	7		Multiple models	HD and Thermal (IR) camera	Deployed from CTV/SOV	blade exterior (coating)
9	Drone Base	WT Drone Inspection and Life Cycle Management	Drones with thermal imaging capability	Commercial				HD and Thermal camera	Deployed from CTV/SOV	blade, tower
10	Aerodyne Measure	DT^3	Robotic blade care with AI driven defect detection. Drone with UT sensor; also crawler with test, clean, repair capabilities	Commercial			An average of 8 onshore turbines can be inspected daily (exterior) with automated flying waypoints and distance lock. Drones equipped with HD cameras and capability of locking the camera onto target to capture 1 mm/pixel resolution. Crawler lowered via rope from the nacelle or inside the hub.	UT and Thermal Imaging (IR); LPS testing; blade cleaning attachment; blade LE repair attachment	Drone deployed from CTV/SOV; crawler deployed from inside the hub by a technician	blade exterior and interior
11	Apellix	Opus X4 NDE aerial robotic system	Drone with UT sensor	Commercial		The Apellix NDE Opus X4 DFT (dry film thickness) aerial robotic system is a National Association of Corrosion Engineers (NACE) Innovation of the Year winner.	Height: Up to 100 m (330 ft) above ground level, Endurance: Over 100 separate site measures per hour with all-day flight via ground power (no battery changes), operable in winds up to 12 knots (14 mph), Capabilities: configurable for wide temperature ranges and wall thicknesses, requires only basic piloting skills, Output: Real-time test results with customizable downloads	UT sensor and HD camera	Deployed from CTV/SOV	blade, tower, OSS

12	ABJ	ABJ Windvue	Drone with thermal imaging (IR), ultrasonic sensors (UT), laser shearography and acoustic emissions sensor options	Commercial			ABJ provides drones equipped with ultrasonic testing and/or active infrared thermography techniques to detect anomalies, cracks, voids in rotor blade skins	UT sensors, HD and Thermal camera (IR)	Deployed from CTV/SOV	blade coating inspection, blade skin damage detection
BELOW WATER										
13	Kongsberg Maritime	HUGIN (1000, 3000, 4500, Superior)	AUV	Commercial	Since early 2000's	"HUGIN AUVs have surveyed most of the major deepwater offshore oil and gas fields world wide...Field operations have taken place world wide from arctic to tropical areas. More than three times around the equator in line kilometers of commercial work was already accumulated by 2006."	Depth: 1,000 m, 3,000 m, 4,500 m, 6,000 m Energy: 15 kWh, 45 kWh, 60 kWh, 62.5 kWh Weight: 650-850 kg, 1400 kg, 1900 kg, 2,200 kg	Comprehensive suite of payload sensors: multibeam echo sounder (MBE), side-scan sonar (SSS), sub-bottom profiler (SBP), CTD, ADCP, + other sensors	launched from vessel	all subsea structures, including mooring lines
14	Kongsberg Maritime, NTNU, Statoil	Eelume	AUV (robot arm)	Commercial	In November, 2021, Argeo signed the first commercial contract for Eelume.	Kongsberg has been actively involved in Eelume since the company was founded in 2015 and has brought almost 30 years of experience from their HUGIN AUV. Argeo has selected Eelume in the first commercial contract to be signed for this innovative technology.	Maximum operating depth: 500 m, Robot length: 2.5 m, Tether cable length: 500 m, Robot diameter: 20 cm or (including thrusters) 49 cm, Robot weight in air: 70 kg, Robot maneuverability: 6 degrees of freedom.	HD video cameras, HD inspection cameras, optional sensor and tooling modules (torque tools, grippers, brush tools)	launched from vessel or underwater docking station	external equipment
15	Oceaneering International, Inc.	Freedom, Isurus	ROV	Commercial	Decades	Oceaneering is the world's largest manufacturer and operator of work class ROV systems.	Depth: 4,000-6,000 m Energy: 50 - 100 kWh battery capacity Weight: 2,200 - 2,700 kg	Laser imaging, Still camera w/flash, hydrophone, altimeters,	launched from vessel	All subsea structures, including mooring lines
16	Hydroid (a Kongsberg company), Oceanographic Systems Lab (OSL) in the Woods Hole Oceanographic	Remote Environmental Monitoring Units (REMUS) (100, 600, 6000)	AUV	Commercial	Since early 2000's	Commercial use includes offshore (oil & gas), environmental monitoring, hydrography, and search and recovery applications.	Depth: 100 m Diameter: 19 cm Weight: 37 kg Depth: 600 m Diameter: 32.4 cm Weight: 240 kg	Side-scan sonar, digital camera with strobe light, bathymetry profiling sonars, conductivity and	launched from vessel	external equipment

	Institution (WHOI), Office of Naval Research						Depth: 6,000 m Diameter: 71 cm Weight: 862 kg	temperature sensors		
17	General Dynamics Mission Systems	Bluefin-12	UUV	Commercial		US Navy deployed the UUV under the ice in the arctic circle	Depth: 200 m Energy: 4x 1.9 kWh Li-ion batteries Weight: 250 kg	Integrated suite of sensors	launched from vessel	External equipment shallower than 200 m
18	ECA Group	A9 A18	AUV	Commercial		Multi-missions autonomous underwater vehicles for military and commercial applications including critical infrastructure protection, Rapid Environment Assessment (REA), search and rescue operations, Intelligence, Surveillance, Reconnaissance (ISR), data acquisition, deep water survey & inspection.	Diameter: 23 cm Length: 2-2.5 m Weight: 70 or 100 kg Endurance: up to 20 hours Depth: up to 200 m Diameter: 18 cm Length: from 4.5 m Weight: from 442 kg Endurance: up to 24 hours Depth: up to 300 m	Interferometric Side Scan Sonar, Synthetic Aperture Sonar (SAS), Video, CTD, environmental sensors (e.g. turbidity, PH, DO or fDOM)	launched from vessel	Underwater structures (e.g., substructures, subsea cables and other subsea equipment)
19	ECA Group	H2000	ROV	Commercial		Used by the French Navy	Depth: 2,000 m Energy: 40 kVA required Weight: 900 kg	variety of viewing & navigation systems and sensors	deployed from vessel	Underwater structures (e.g., substructures, subsea cables and other subsea equipment)
20	SAAB	Sabertooth (single hull and double hull)	AUV/ROV Hybrid	Commercial		The Sabertooth system has been demonstrated at NASA´s Neutral Buoyancy Laboratory (NBL). As part of a symposium, Sabertooth was tested in the NBL's 23.5-million-litre tank in Houston, Texas.	Dimensions: 3.6 x 0.66 x 0.45 m (single hull) 4 x 1.35 x 0.67 m (double hull) Depth: 1,200 m (single hull) or 3,000 m (double hull) Weight: 800 kg (single hull), 2000 kg (double hull) Battery: 12kWh (single hull), 30 kWh (double hull)	SM7 cleaning brush, high resolution camera, low light camera, bathymetric system for side scan imagery and sub-bottom profiles, HLK-HD5 manipulator arm, torque tool.	Underwater docking system rated to a depth of 3000 m providing a battery recharging facility and protection for the vehicle for over six months.	Underwater structures (e.g., substructures, subsea cables and other subsea equipment)
21	SAAB	Cougar-Xti	ROV	Commercial		Saab Seaeye Cougar Xti has been acquired for deployment by companies such as Kaiyo Engineering,	Depth Rating: 2000 m Length 1515: mm Height 790: mm Width 1000: mm Launch Weight: 435 kg	HD camera, bathymetric system , scanning sonar, multibeam sonar, heavy duty	Deployed from vessel. Multiple deployment systems, including Tether	Underwater structures (e.g., substructures, subsea cables and other

						Timsah Shipbuilding Company, and CCC (Underwater Engineering) S.A.C.		manipulator arm system, compact cutter for steel wire ropes, rotary cutter for hoses and cables, cleaning brush, water jet system for cleaning operations, and UT system.	Management System (TMS) with 200 m of fiber optic tether allowing for the deployment of the ROV at working depth.	subsea equipment)
22	4Subsea	SMS Strain Sensor; SMS Guard; SMS Motion; 4Insight (ML data analysis)	SMS sensor	Commercial	<1		Weight: 95 g, 12 kg, 9.4 kg Service life: 12 months Battery: 2 x 26 Wh	strain sensors, IoT enabled	Installed by technician on WTG (above water), or ROV or diver (below water)	WTG tower
23	Kawasaki Heavy Industries	SPICE (Subsea Precise Inspector with Close Eyes)	AUV	Commercial in 2021	<2	The SPICE (Subsea Precise Inspector with Close Eyes) is an autonomous underwater vehicle that will primarily be used for the inspection of underwater oil and natural gas pipelines, though it is expected to also support inspection and testing in the offshore wind sector.	Dimensions: 4.5 m length, 2 m width (SPICE), 5 m long and 2 m wide (docking station). Max operating depth: 3000 m. Speed: 4 knots (travel), 2 knots (while performing a task).	Robotic arm	Deployed from the underwater docking station.	Underwater structures (e.g., substructures, subsea cables and other subsea equipment)
24	Pharos Offshore Group	UTV400	Trenching ROV (TROV)	Commercial in 2017	4	The 400hp Trenching ROV is capable of undertaking all aspects of cable maintenance, seabed survey and cable burial work in the offshore oil, gas, renewable and telecommunications markets.	Dimensions: 4.3 m length, 3.2 width, 2.8 m (Free-Fly mode), 4.3 m length, 3.7 width, 2.7 m (Tracked mode) Weight: 8000 kg (Free-Fly mode) 9200 kg (Tracked mode) Max operating depth: 2500 m Trench capability: 2 m max depth, soil dependent.	Cameras, cable gripper, sonar, cable tracking system, cable detection sensors, target acquisition arm, bathymetric system, burial tool	Deployed from vessel using a launch and recovery crane.	Underwater structures (e.g., substructures, subsea cables and other subsea equipment)
25	Vaarst (the technology wing of Rovco), Offshore Renewable Energy (ORE) Catapult	SubSLAM X2 (the AUV3D project)	ROV	Available (fixed-term 3-year license)		SubSLAM X2 is the first real-time intelligent data collection system that delivers underwater live 3D point clouds and	Dimensions: 359 x 247 x 140 mm Weight: 8.55 kg (shallow unit), 12.7 kg (deep unit) Operating depth: 300 msw (shallow unit), 1000 msw (deep unit) Scan time: Immediate and live	Machine vision sensors, fast onboard processors	SubSLAM X2 is deployable from any ROV.	Foundation

						navigation with sub-millimeter precision.	result Test condition: 1.2 m visibility Error over 1 m: ±0.67mm			

Register 7-2: Columns 1,11-19

Column #	1	11	12	13	14	15	16	17	18	19
#	**Manufacturer/ Service Provider or Operator**	**Maintain (clean)**	**Test**	**Repair**	**Safety Impact (compared to manual inspection)**	**Level of autonomy (see below for "Level" key)**	**Used for WT? (0=none, 5=extensive)**	**Used for offshore WT? (0=none, 5=extensive)**	**associated risks**	**Associated benefits, including Economic**
ABOVE WATER										
	MANUFACTURERS									
1	Superdroid robots		survey hazardous situations	Can transport or manipulate heavier objects. Potential repairs (bolt tightening) with articulated arm.		1	0	0	Potential loss or damage of robot or equipment if contact with turbine structure fails.	
2	Bladebug	Performs preventative maintenance tasks out of the line of sight of technicians	Modular design of robot body can accept different non-destructive testing equipment	Defects in the blade skin can be detected and repaired.	De-risk activities performed by rope access technicians (e.g. harsh environments)	1	4	3	Potential loss or damage of robot or equipment if contact with turbine structure fails.	Preventative maintenance and early-stage repairs reduce downtime and associated costs.
3	Rope Robotics	Clean and sand blades using articulated arm fitted with cleaning fluid/wiper or sand paper	Measure blade leading edge erosion	Repair blades (articulated arm with attachments)	Eliminates need for rappelling down the blade for inspection and/or leading edge repair	1	5	1	if robot loses contact with blade, swinging robot could cause damage	Reduces downtime associated with blade cleaning and repair
4	EddyFi		Crawler is readily adaptable for non-destructive testing sensors for specific job requirements.		Reduces or replaces the need for rope access, working at heights or in confined spaces, and scaffolding.	2	2	2	Potential loss or damage of robot or equipment if contact with turbine structure fails.	Improved data quality and repeatability ensures accurate operations and reduces costs.
5	Skygauge Robotics		Assessments are conducted using both visual		Assessments and tests may be conducted in harsh environments	3	0	0	loss of drone	Improves operational efficiency over traditional access and testing methods.

			inspections, and real-time ultrasonic readings.		that would pose risk to personnel.					
6	Skyline Drones		Test thickness with UT			3	0	0	loss of drone	
	SERVICE PROVIDERS									
7	SkySpecs		Testing for cracks, voids or other damage with IR, RGB			3	5	3	loss of drone	Routine inspections reduce costs of down-time and crew and cranes after blade collapse.
8	Precision hawk		Testing for cracks, voids or other damage with IR, RGB			3	0	0	loss of drone	Reduces inspect. Cost by up to 80% over manual.
9	Drone Base	Assets are inspected with thermal imaging sensors for conditions to be maintained or repaired, such as leading edge erosion, impact damage, debonding, delamination, and top coat damage.			Minimizes need for rope climbs and handheld cameras, which prove to be dangerous.	3	5	2	loss of drone	Drone captures high-quality images, minimizing turbine downtime and reducing inspection costs.
10	Aerodyne Measure	Removes dirt (including drain hole cleaning), paints blade. Covers 6 m/minute.	Blade testing includes, thermal imaging to detect voids or cracks, and ultrasonic inspection to measure skin thickness. Tests for conductivity of LPS from blade exterior, 10 mins/blade	Repair blade leading edge	Eliminates need for technicians to work on ropes.	3	4	3	loss of drone; equipment failure	Aerodyne reports operation cost savings of 35%, and 50% cos saving in defect marking and categorization. Cloud-based infrastructure inspection and management solutions and access to offshore and onshore blade specialists are also offered.
11	Apellix	Data can be imported into Preventative Maintenance Checks and Services (PCMS) and other systems.	Assets are tested while in service through both visual assessments (via HD video) and wall thickness measurements (via UT readings).		Assessments and tests can be performed in hazardous spaces and at great heights, removing risks of falls.	3	5	0	loss of drone	Measurements can be collected and streamed in real-time and data can be imported easily into other systems.

12	ABJ		Testing for cracks, voids or other damage with IR, RGB			3	5	3	loss of drone	Turbine only needs to be turned off for a few minutes rather than hours
BELOW WATER										
13	Kongsberg Maritime		Environmental Monitoring, seabed mapping			3		2		reduces inspection costs
14	Kongsberg Maritime, NTNU, Statoil	Light maintenance, including cleaning, in confined spaces not accessible by conventional underwater vehicles.		Light repairs with precision hovering and maneuvering even in strong currents.	The robot can live and operate permanently underwater regardless of weather conditions, improving safety of intervention operations.	3		1		Cost savings through reduced use of expensive surface vessels, which are needed to support such operations today.
15	Oceaneering International, Inc.		Tide monitoring, asset analysis, seabed mapping, light intervention	Can execute cable lay, deploy robotic crawlers, cable messenger wire hook-up	Monitoring and surveying activities can be performed in harsh weather conditions .	Can be 2 or 3	0	3		Cost savings through increased productivity and endurance since these vehicles can investigate a larger area over a longer period of time in harsher conditions.
16	Hydroid (a Kongsberg company), Oceanographic Systems Lab (OSL) in the Woods Hole Oceanographic Institution (WHOI), Office of Naval Research				Monitoring and surveying activities can be performed in harsh weather conditions and in areas with explosives.	3		0		Cost savings through increased productivity and endurance since these vehicles can investigate a larger area over a longer period of time in harsher conditions.
17	General Dynamics Mission Systems		environmental sensing		Can navigate autonomously under ice	3	0	0		Cost savings through increased productivity and endurance since these vehicles can investigate a larger area over a longer period of time in harsher conditions.
18	ECA Group				Activities can be performed in close vicinity to explosives without triggering them, keeping crew out of danger. Hazards can also be detected, including explosives, pollutants, and seabed features.	3	0	0		Devices can carry out missions requiring long operating endurance with high stability, minimizing effects of waves compared to towed systems.

19	ECA Group		Light intervention			3	0	0		reduces inspection costs
20	SAAB			Sabertooth is capable of autonomous inspection, maintenance and repair (IMR) of subsea installations, tunnels and for offshore survey work.		3	0	0		Sabertooth can swim autonomously to the docking unit and remain there 24/7 for more than six months without maintenance, eliminating cost of surface vessels.
21	SAAB			Cougar-Xti accommodates a wide range of quick-change tooling skids, ideal for survey work, IRM, drill support, light construction projects, and salvage support operations.		3	0	0		Cougar-XTi leads a new generation of compact, highly flexible and extremely powerful electric ROVs that offer users the ability to undertake a wider range of demanding tasks at lower operating costs.
22	4Subsea	Minimizes cable failure via sensor monitoring, which can warn against cable failure 5 years in advance Can be coupled to SMS Gateway (topside) or SMS Motion (subsea) to provide synchronized strain & motion data	Document safe extension of wind farm life by using sensors that confirm the wind farm can keep operating past its life expectancy. Use machine learning that can do anomaly detection		Reduces need for in-person inspection both AWL and BWL	2 (AWL) 3 (BWL)	0	4	If sensor fails, then operator lacks real-time loads data	reduces inspection costs, reduces downtime by indicating potential failure in advance, allowing more time to prepare for repair. Can increase wind farm life by 20-30%
23	Kawasaki Heavy Industries		Inspect: SPICE is equipped with a still camera and robot arm for extreme close-range visual inspections. For laid pipelines, inspections are performed with radar and sonar. The robot arm could also potentially facilitate measurements.		SPICE reduces the risks to support personnel by eliminating the need to launch and/or recover the device for recharging.	3	0	3	SPICE halts inspections when it detects low battery levels and returns to the docking station and commences battery recharging using a non-contact electrical charger (without the need for resurfacing). Operators should, therefore, account for potential interruptions for recharging.	SPICE uses a uniquely devised Kawasaki algorithm to support search and tracking operations. While the robot arm is in operation, SPICE can automatically adjust its position to avoid obstacles or follow a structure.

24	Pharos Offshore Group	Supports maintenance tasks:	Inspect and Repair: The 400hp Trenching ROV supports inspection, repair and maintenance tasks, with the ability to deburr, cut and recover a multitude of subsea products with enhanced efficiency.	Supports repair tasks: can deburr, cut, recover underwater cables or other subsea equipment, for repair		2 or 3	0	2	The TROV is an essential part of cable installation and maintenance due to its small deck requirements and ease of maintenance.	
25	Vaarst (the technology wing of Rovco), Offshore Renewable Energy (ORE) Catapult		Inspection: SubSLAM X2 is designed to replace video, laser scanning, and the use of other external sensors for imaging. SubSLAM X2 is equipped with machine vision sensors and fast onboard processors that generate real-time 3D point clouds (models) of underwater structures and the surrounding seabed. These 3D models can be streamed to any device via Vaarst's Intelligent Data Delivery Platform.		SubSLAM X2 generates live 3D reconstructions with < 1 mm accuracy, allowing operators to be more reactive to potential issues and ensure the safety of personnel while a campaign is still underway.	2	5			The real-time 3D models generated by SubSLAM X2 help operators quickly identify issues and plan repairs. Access to SubSLAM X2 is currently offered as fixed-term 3-year (minimum) licenses with an annual license cost. One of the benefits of licensing is free access to continuous updates from future software modules.

List of Acronyms	Definition
ADCP	acoustic doppler current profiler
AUV	autonomous underwater vehicle
AWL	above water line
BWL	below water line
CTD	Conductivity, Temperature and Depth measurement device used
CTV	Crew Transfer Vessel
DTMS	Distributed temperature measurement system
IR	Infrared thermography
IRM	integrated radar measurement sensor
MBE	Multibeam echo sounder
MPI	Magnetic particle inspection
RGB	"Red, Green, Blue" feature of visual cameras to produce full-colo
ROV	remotely operated vehicle
SBP	Sub-bottom profiler
SMS	Smart monitoring sensor
SOV	Service Operations Vessel
SSS	Side-scan sonar
UUV	Underwater unmanned vehicle
UT	Ultrasonic testing

Level of Autonomy	Description
0	Full manual operation (no autonomy, no RIT)
1	RIT is operated from the WTG nacelle/hub (no blade entry required)
2	RIT is operated from the WTG base platform (no tower climb required)
3	RIT operated from a nearby vessel (no transfer to WTG platform required)
4	RIT is operated from shore, for limited set of scenarios
5	RIT handles all operational decisions with no input from a human at all

Register 8: Register of remote inspection technologies **under development**

Explanatory Note:

This register presents the remote technologies under development (not yet commercially available, or proposed extension of a commercial product). The Register focuses on the individual technologies that were reviewed, as opposed to the broader questions regarding situations where RITs would be insufficient, or overall potential challenges with remote inspections. These important topics will be discussed in the accompanying report.

Register has been split into TWO tables (for readability), where Register 8-1 includes Columns 1-10, and Register 8-2 includes Columns 1, 11-19. For unified table and complete workbook, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

Register 8-1: Columns 1-9

	1	2	3	4	5	6	7	8	9
#	**Manufacturer/ Service Provider or Operator**	**equipment name**	**Remote Inspection Technology (RIT) Type**	**Development Status**	**Detailed Description (future release date, capabilities, etc.)**	**Technical Specifications**	**Installed RIT tools**	**Deployment method and additional equipment required**	**Components (new or current) that can be addressed with future RIT**
ABOVE WATER									
1	Mitsubishi	EX ROVR	crawler robot with robotic arm	Plan to commercialize by 2022	Explosion-proof certified unmanned ground vehicle that will be commercialized by 2022. Intended for inspection of oil refineries. Capable of collecting images, thermal images, gas concentration, temperature, acoustic mapping, and sound. In the future will have an emergency button and valve operation. Robot gathered info is stored and managed on the Cloud.	Gripper arm: 6.6 lb. and 39.1 inches. Speed: 1.2 km/hr. Hardware specifications: 27.5-47.2 in length, 17.7 in width, 19.7 in height, 165 lbs.	Camera, IR camera, leak detection, Lidar, gas detector, integrated IMU, distance sensor	Deployed from subsea charging station, using wireless antenna. The robot setup and control for mapping, routing, and autonomous traveling inspection are remotely implemented.	Turbine electrical components (Nacelle), OSS
2	Offshore Renewable Energy (ORE) Catapult	Bladebug	crawler robot	Offshore prototype demonstration 2020	Crawler with 6 independent legs that use suction to maintain connection to the blade surface		Existing: camera, UT NDT, Future: composite repair patch capability	Deployed from nacelle	Blade exterior
3	Fraunhofer IWES	Acoustic emission measuring system	Monitoring sensors	Conducting lab tests in rotor blade test facility	Acoustic emission measuring system aimed to provide automated and reliable detection and classification of structural damage for wind turbine rotor blades		Piezoelectric sensors and acoustic emission attached to inner blade surfaces	Attached to the inner surface of rotor blade.	Rotor blades
4	Fraunhofer IWES	Drones with Mobile Thermography	Drones	Completed initial lab tests.	Researchers are working to detect subsurface defects in composite materials by attaching thermal imaging cameras to drones.		Thermal imaging cameras	Deployed from vessel (CTV/SOV)	Rotor Blades
5	Innovate UK, Perceptual Robotics	Automated Takeoff and Landing	Drone	Development	Perceptual Robotics is partnering with Innovate UK for the MIMRee project to use their drone as a way to deploy a crawler (BladeBug) onto a turbine blade. The drone		LIDAR, camera	Deployed from an unmanned surface vehicle.	Rotor Blades

					will carry the crawler from an unmanned surface vehicle and attach it to the blade				
6	Innvotek, Mapair, ORE Catapult	Firefly Inspect	Drone	First successful trial in 2022.	Firefly Inspect uses active thermography to inspect composite structures, such as wind turbine blades.		IR camera, OptiTrack motion capture tech, 1,000W heat lamp, AI	Deployed from vessel (CTV/SOV)	Rotor Blades
7	ESVAGT, Siemens Gamesa, Orsted	Drone Based Tool Delivery	Drone	In development	ESVAGT, Siemens Gamesa, and Orsted are developing a drone-based solution for the delivery of spare parts and tools from vessel to offshore wind turbine		Attachments able to grab and carry 3-4 kg	Deployed from ESVAGT's Service Operation Vessels	The whole turbine
8	EnBW, DLR	Drone Based Tool & Material Delivery	Drone	Research Project from 2022-2025	EnBW and DLR are working to fly service technicians by air taxi to their assignment on a wind turbine while their tools and materials are transported by cargo drone.		Attachments to carry tools and materials	Deployed from shore	The whole turbine
9	DNV, University of Bristol, Perceptual Robotics	Automated Data Processing	Processing system	Early research phase	Automated data processing system (software) that provides automated verification, validation and processing of inspection data gathered by other RIT	SLAM, 3-D tracking tech		Software platform	Any part that is inspected or monitored by RIT
10	Bureau Veritas (BV), Dassault Systèmes, Offshore Renewable Energy (ORE) Catapult	Veristar AIM 3D Digital Twin	Digital Twin	3D digital twin under development	In 2015, BV and Dassault Systèmes collaborated to develop Veristar AIM 3D, a digital twin conceived to be used from the design stage, through construction, and operation, to reflect and predict the condition of any asset. BV has since partnered with Offshore Renewable Energy (ORE) Catapult to jointly develop a 3D Digital Twin of ORE Catapult's Levenmouth Offshore Wind Demonstration Turbine.	Veristar AIM 3D is based on the Asset Integrity Management services of Bureau Veritas and the 3DEXPERIENCE platform of Dassault Systèmes. Digital twin combines real-world operating data with numerical modelling.	Veristar AIM 3D uses condition monitoring data, manual inspection data, and 3D modelling to provide insights via 2D and 3D diagrams and an asset management dashboard.	Veristar AIM 3D is a software platform developed and utilized as a digital technology.	Turbine
11	DNV	WindGEMINI	Digital Twin	Advancements under development	A wind turbine digital twin that analyzes data from wind farms automatically. System ingests SCADA signals from the wind turbines, processes them in real time to provide information on turbine performance, health, remaining component life.	Gemini digital twin combines real-time operating data with numerical modelling.	WindGEMINI combines SCADA, condition monitoring, and inspection data with a comprehensive system of algorithms that provide insights on performance, power curve, component failures, remaining life, and long term production forecasts	WindGEMINI is a software platform developed and utilized as a digital technology	Turbine
BELOW WATER									
11	University of York, University of Strathclyde, Supergen, PicSea, Catapult and EC-OG	Robofish	AUV	Development	The "Autonomous Biomimetic Robot-fish for Offshore Wind Farm Inspection" is a modular bio-inspired autonomous underwater vehicle with visual inspection, acoustic communication, and navigation capabilities. Design of the first RoboFish prototype was completed in December 2020. Testing of the RoboFish at the ORE	Structures: Articulated with watertight body, head, and tail segments with 3D printed parts. Internal diameter: 93 cm (body segment), 10 cm (head). Length: Variable to	Camera, acoustic range-finder	Deployed from vessel or underwater docking station.	Foundations and other subsea equipment

					Catapult testing site in Blyth was planned for 2021.	modifications, 42.2 cm (body segment). Joints: Magnetic coupling joint design. Operating depth: 500 m. Power: Self-managed battery power, subsea power hub (underwater generator) used with docking.			
12	Soil Machine Dynamics Ltd (SMD), Rovco Ltd	Next generation Atom EV Work Class ROV (WROV)	Work Class ROV (WROV)	Development	In March 2022, subsea equipment manufacturer Soil Machine Dynamics Ltd (SMD) and intelligent offshore services provider Rovco Ltd signed a Letter of Intent for the first of a fleet of vehicles designed to interface with Rovco's latest computer vision and AI capabilities.	Dimensions: 2600mm Length, 1500mm Width, 1560mm Height. Weight in air: 2000 kg. Max operating depth: 3000 msw (Standard), 1000, 2000, 4000, 6000 msw (Optional)	Cameras, manipulator, grabber, surveying instruments, sensors	Deployed from vessel.	Subsea cables and other equipment
13	EM&I	HullGuard® Diverless ICCP System	Corrosion protection	Development	The HullGuard® diverless ICCP (Impressed Current Cathodic Protection) system (patents pending) is designed for lifetime protection of underwater hulls from corrosion below the water line.	HullGuard® consists of a cylindrical anode that retracts into the hull through a special port welded to the inside of the asset hull. HullGuard® anodes can serve as replacements for conventional anodes and can be installed and maintained at any stage in the asset's life.	Anodes	HullGuard® is installed with a 3-4 person team. It is easy to install during construction, may be readily retrofitted to existing assets, and is easy to maintain throughout the assets' operational life.	Foundations
14	EM&I	NoMan® Inspection System	Robotic arm	Development	The NoMan® confined space inspection system (patents pending, proven) is a revolutionary new method for inspections of ballast, flotation and other confined spaces using robotic cameras, laser scanning and other specialized inspection tools.		Robotic arm, optical system (high-performance video and still camera system), and laser system	NoMan® is deployed using by a 2-person team on location.	Water ballast tanks
15	DNV	Remote Hull Surveys with Virtual Reality	Autonomous vehicle	Development	DNV is developing an autonomous vehicle (drone) that will reduce the need for in-person hull inspection by creating a 3D model of the hull that can then by inspected using Virtual Reality		indoor positioning technology, camera, image mapping algorithm, Virtual Reality (VR) technology, measurement gear.	The 3D imaging technology will access the hull structure via autonomous vehicle.	Floating foundation
16	DNV	Hull Insights	Machine learning algorithm (software platform)	Development	Hull Insights is a dashboard providing detailed information on the predicted condition of hull structures and the probability of weak spots.	Hull Insights implements a machine learning algorithm and uses vessel design and construction information, recordings from past	Hull Insights presents findings on a dashboard on the Veracity My Services portal.	Hull Insights is developed and utilized as a digital product (software platform).	Floating foundation

						surveys, and operational and environmental data to predict the condition of hull structures.			
17	HonuWorx, ORE Catapult	Ridley Loggerhead	Autonomous platform (mothership) for large subsea robots	Development	HonuWorx is developing a series of robotic deployment systems. The first of these systems, Ridley, is an autonomous submersible deployment and operations platform. Ridley can transport large robots and remotely operated vehicles (ROVs) to offshore sites and release them directly under the water. The successful development of Ridley will inform HonuWorx's development of the Loggerhead concept. Loggerhead will utilize the autonomous mothership as a mobile power and communications hub for ROVs and AUVs. The Ridley system will be tested at ORE Catapult's facilities.	Loggerhead will measure approximately 15 m in length.	Ridley uses cloud-based distributed mission control and automation software for coordinating multiple platforms with communications technologies that can utilize satellite, 4G and 5G as best suits each location at sea.	Ridley is towed to the worksite by small vessels. Once at site, Ridley submerges to deploy subsea robots without the need for crane drops. Deployment is possible in rough water.	Foundation and other subsea and splash zone components
18	Innvotek, Offshore Renewable Energy (ORE) Catapult (ROBFMS and iFROG projects)	Amphibian	ROV	Development	Amphibian is a robotic platform for inspection and maintenance of offshore structures. It was developed by Cambridge's Innvotek under the ROBFMS and iFROG projects and was fully tested and validated in 2020 at ORE Catapult's National Renewable Energy Centre. The Innvotek team have worked closely with the European Marine Energy Centre (EMEC) and ORE Catapult under separate projects (ROBFMS and iFROG) to develop and ready their solution for operation in real-world conditions.	Dimensions: 870 x 600 x 230 mm Weight: 42 kg (not including umbilical) Payload weight: 25 kg Operating depth: Up to 60 m Power and communications tether length: 60 m (standard) Design: Modular magnetic wheels and rubberized tire (constant adhesion with the climbing surface and good traction without damage)	HD camera, NDT systems (including Ultrasonic Testing, Phased Array Ultrasonic Testing, Pulsed Eddy Current Testing), high pressure water jet module, and automated weld following system	Amphibian will be deployed from a vessel and requires 2 people for deployment and 1 person for control.	Foundation
19	MarynSol, HydroSurv, Offshore Renewable Energy (ORE) Catapult	SeaWynd	USV	Development	SeaWynd is an integrated, multi-sensory platform that will enable the remote inspection of marine turbine structures from the seabed up to the splash zone. This technology combines MarynSol's advanced automated data solution, SeaSmart, with HydroSurv's state-of-art REAV class Unmanned Surface Vessels (USVs). Tests of the technology's capabilities have been conducted at ORE Catapult's Levenmouth Offshore Wind Demonstration Turbine.	SeaWynd combines the USV Rapid Environmental Assessment Vessels (REAV) designs by HydroSurv with several subsea and above-water profiling technologies.	HD camera, LiDAR, Photogrammetry, multi-beam sonar, fully automated data-point integration, time lapsed change detection monitoring, real time data delivery	HydroSurv's USVs for nearshore and coastal applications may be launched from the beach s.	Foundation (seabed to splash zone)
20	MarynSol, Offshore Wind	CableWynd	AUV	Development	CableWynd is an autonomous cable inspection technology to be developed by		High-resolution sonar, ultra-sensitive		Subsea cables

	Industry Council (OWIC)				MarynSol. In 2021, MarynSol announced that it won grant funding from the Offshore Wind Industry Council (OWIC).		magnetometry, hydrographic survey, fully automated data-point integration, time lapse change monitoring		
21	DNV	Smart Mooring Monitoring (SMM) system	Software platform	Pilot testing is underway	The SMM System is a turnkey digital solution which can replace existing mooring monitoring systems. It requires a minimal IT hardware installation and can provide more accurate predictions than physical tension monitoring systems.	Software platform with minimal IT hardware.	No dedicated sensors or other tools required.	IT hardware installed in tower base.	Floating platform mooring lines

Register 8-1: Columns 1,10-16

	1	10	11	12	13	14	15	16
#	**Manufacturer/ Service Provider or Operator**	**Capabilities (incl details): * inspect * test * repair**	**Safety Impact (compared to manual inspect.)**	**Level of autonomy (refer to "Task 2 Survey Notes")**	**Planned for use in offshore WT? (0=none, 5=extensive)**	**Benefits of future RT**	**Associated risks of future RT**	**What potential challenges might arise using new RIT?**
1	Mitsubishi	Inspection: The robot has been deployed as a disaster response measure in tunnels and oil/gas/chemical plants for gathering reliable information safely and effectively. Capable of digital inspection data analytics; data is fully researchable & trendable (IoT). Can climb stairs, avoid obstacles, open doors	Reduces the need for human to be exposed to explosives/dangerous conditions during inspection	can be 2 or 3	0	Avoidance of non-value add & highly repetitive tasks which frees human operator for more productive jobs. Preventing unplanned shutdown by more frequent inspection	Small changes/inconsistencies in the area mapping that allow the RIT to be autonomous can result in error/failure. The battery may die before the RIT can return to its charging station.	Storing and managing info on the cloud can be a security risk.
2	Offshore Renewable Energy (ORE) Catapult	Inspection, Testing, Maintenance: Performs preventative maintenance tasks out of the line of sight of technicians. Modular design of robot body can accept different non-destructive testing equipment. Defects in the blade skin can be detected and repaired.	De-risk activities performed by rope access technicians (e.g. harsh environments)	1	3	Preventative maintenance and early-stage repairs reduce downtime and associated costs.	Potential loss or damage of robot or equipment if contact with turbine structure fails.	
3	Fraunhofer IWES	Inspection, Monitoring: Monitor and inspect rotor blades to catch early damage. Sensors are used to detect material changes using high and low frequency acoustic emission. The measurement computing device that	Reduces the need for humans to propel up and inspect rotor blades. Helps catch damage early to prevent significant damage.	3	5	Adaptation of the technique to reflect the particular material characteristics of rotor blades and their application scenarios should produce a cost-effective structure monitoring system,	Could detach from the blade and stop working.	Unclear at what stage the RIT gets installed; can it be attached to rotors already in use or does it have to be incorporated

		collects and analyzes the sensor data is integrated in the rotor hub. Using sound waves it is possible to pinpoint the source of the damage.				which will cut costs in the long term. Works to catch damage early to prevent major structural failure. Surface damage to the blades can diminish output, so catching it early is also cost-effective.		during the building phase?
4	Fraunhofer IWES	Inspection: Drones with mobile thermography would be able to detect subsurface defects such as delamination, inclusions, faulty bonding in the loadbearing web-flange joints, and shrinkage cavities. Structure defects in rotor blades cause friction which generates heat that can be detected through thermal imaging.	Reduces the need for humans to propel up and inspect rotor blades. Helps catch damage early to prevent significant damage.	3	5	Subsurface damage is not as easy to detect with a human eye, so works to catch damage early to prevent major structural failure. Surface damage to the blades can diminish output, so catching it early is also cost-effective.	The drone can fall out of the sky or experience turbulence from nearby turbines.	
5	Innovate UK, Perceptual Robotics	Inspection, Repair: Deploy crawlers used for inspection and repair. UAV drones utilize advanced onboard LIDAR and imaging to locate a turbine, identify its orientation, and generate a flightpath.	Allows for a safer way to deploy a crawler robot onto the blades, especially during harsh weather and sea conditions	3	5	Will allow for a streamlined autonomous inspection and repair of blades by having unmanned surface vehicles, drones, and crawlers work together to complete autonomous inspection and repair.	There is a lot of room for error by depending on three different RITs to autonomously work together to accomplish a task. One error can throw off the whole process.	Could this streamlined process be adaptable to different RITs being incorporated into the process?
6	Innvotek, Mapair, ORE Catapult	Inspection: Firefly Inspect can hover above wind turbine blades using a 1,000W heat lamp to test for defects. The active thermography module enables capture of variations in surface temperatures of blades when heated, revealing hidden imperfections that were not visible on the surface. They have demonstrated their ability to hover autonomously and maneuver close to vertically suspended wind turbine blades. Received thermal image data is processed using matching learning algorithms. A report is automatically generated identifying the type and location of the defects and all data and reports are securely stored online Firefly Inspects ability to detect hidden structural defects, automatically locate their position, using artificial intelligence, will help	Reduces the need to manually scale structure to find visible defects, which improves personnel safety, as well as makes turbine damage more preventable.	3	5	Is more safe and cost-effective than manual inspection of the blades. The autonomous nature of the drone makes image better and clearer than drones operated by pilots. Catching defects early can help extend the lifetime of a turbine.	The drone can experience turbulence from surrounding active turbines and go off course or fall from the sky.	

		operators make informed decisions and extend the service life of composite components.						
7	ESVAGT, Siemens Gamesa, Orsted	Maintenance, Repair: Tools and spare parts weighting up to 3-4 kg will be transported to technicians via drones from a Service Operation Vessel. The goal is to have the drone transport parts between two variable points, following a route that will be adjusted along the way.	Reduces the need for a technician to have to go back down if there is a part missing	2	5	Delivering tools via drone can save a lot of time and make the project more efficient.	The changing weight of the cargo, the wind's impact, and the use of magnetic compass in an offshore wind farm with lots of steel can make controlling the drone difficult	Is it worth investing in this strategy if there is work being done to have repair and maintenance be done autonomously?
8	EnBW, DLR	Maintenance, Repair: Tools and materials will be transported to the wind turbine technicians	Using cargo drones to transport tools and materials directly to the top of a 100-meter wind turbine would eliminate the need for cranes. If service technicians were to travel by air taxis, as passenger drones are called, there would be no need for transfers to the turbines and two-week shifts with overnight stays at sea.		5	Delivering tools via drone can save a lot of time and make the project more efficient.	The changing weight of the cargo, the wind's impact, and the use of magnetic compass in an offshore wind farm with lots of steel can make controlling the drone difficult	There are still a lot of unknowns to be answered such as how offshore wind farms need to be equipped to enable drone use, what a drone landing platform might look like, how a shipping container needs to be designed, and what the communication interfaces might look like.
9	DNV, University of Bristol, Perceptual Robotics	Inspection: Experts in 3D computer vision and image processing, will create algorithms for automated localization of inspection images and defects using SLAM and 3-D tracking technology. Will create AI-based models for defect detection to trial automation of process in a commercial production environment.	Reduces the need for humans to manually look through drone photos/data to determine an issue, could result in human error	3	5	An accurate autonomous data processing system will save time and may improve the likelihood that issues could be caught	Inability for processing system to accurately analyze images	Can be hard to adapt to different images produced by varying RITs
10	Bureau Veritas (BV), Dassault Systèmes, Offshore Renewable Energy (ORE) Catapult	Monitor, Report: Veristar AIM 3D provides data analytics to help make decisions about actual and future asset condition, which informs inspection, maintenance, repair activities and reporting activities.	The use of Veristar AIM 3D enhances safety and reliability of structures by enabling operators to accurately monitor and predict future performance, facilitating maintenance planning.	4	5	Veristar AIM 3D enables operators to reduce unplanned downtime and scheduled maintenance inspections (considering that invasive inspections also pose risks of inadvertently introducing further issues for the asset).		Potential challenges of digital technologies, such as the digital twin, will include ensuring data quality, presenting information in an intuitive manner for operators to understand asset condition and incoming threats and to develop appropriate data-driven decisions.

11	DNV	Monitor, Report: WindGEMINI provides 24/7 access to key metrics and advanced analysis to understand performance, condition, and remaining life of a turbine and its components in order to optimize servicing, inspections, planning of repairs and replacements.	Reduces likelihood of catastrophic failures, reduces downtime and unscheduled maintenance visits.	4	5	WindGEMINI enables operators to reduce unplanned downtime and scheduled maintenance inspections (considering that invasive inspections also pose risks of inadvertently introducing further issues for the asset).		Potential challenges of digital technologies, such as the digital twin, will include ensuring data quality, presenting information in an intuitive manner for operators to understand asset condition and incoming threats and to develop appropriate data-driven decisions.
11	University of York, University of Strathclyde, Supergen, PicSea, Catapult and EC-OG	Inspection: The Robofish is intended for locating and monitoring structural damage (e.g., wear and corrosion) with high agility in proximity. The acoustic range-finder also provides depth estimates by detecting distances from the camera.	The Robofish can perform close-range navigation in situations where traditional alternatives would require tethers and human operators.	3	5	The Robofish has the capacity to apply accelerated algorithms for vision to perform in-situ inspection and analysis while navigating around structures. The Robofish does not use propellers, thereby mitigating the risk of fouling.	Prior to commercial availability, field testing of the Robofish has faced challenges as a result of COVID-19 limitations.	Potential challenges to be addressed in future versions of the Robofish focus on modularity, hydrodynamic performance under different flow conditions, and targeted underwater docking.
12	Soil Machine Dynamics Ltd (SMD), Rovco Ltd	Inspection, Repair: Atom WROVs can integrate with survey instruments and tool packages to provide drill support, survey and light construction duties.	Reduces need for divers	2	3	Atom WROVs can be can be mobilized on vessels and rigs with limited deck space.		
13	EM&I	Inspection, Repair: HullGuard® eliminates the need for conventional methods of inspection, maintenance, and/or replacement of damaged anodes (e.g. dive operations).	HullGuard® requires no diver intervention. As such, its use reduces or eliminates the need for dives and support vessels in harsh conditions, and it also reduces associated carbon emissions.	3	5	HullGuard® addresses the challenges associated with costs and difficulty of maintaining hull protection over the life of floating assets. It has low lifecycle costs and reduces diving costs for inspection and maintenance.	New technologies serving the floating offshore wind industry must adapt to the rapidly evolving regulatory and class requirements.	
14	EM&I	Inspection: NoMan® inserts the optical camera through openings in pre-planned locations on a robotic manipulator to enable close visual inspection of critical components. The laser unit is also positioned by the robotic arm to gather point-cloud data.	NoMan® eliminates the need for human entry into confined spaces, and it reduces carbon emissions associated with travel.	2	5	NoMan®, unlike crawlers, do not cause damage to coatings. It also performs operations faster, with negligible risks of getting stuck in complex structures. It does not need human entry to pilot.	New technologies serving the floating offshore wind industry must adapt to the rapidly evolving regulatory and class requirements.	
15	DNV	Inspection: The autonomous device will be oriented through automatic indoor positioning technology, or optionally be guided through a pre-	Virtually surveying the hull reduces the need to do an in-person tank entry, which is often hazardous due to lack of	2 or 3	5	VR Hull surveys reduce the need for a surveyor's presence, reduces cost and time loss due to travel.	There will be no storage of captured video material, which can result in errors in the 3D	Virtual surveying cannot replace a physical person's ability to touch/feel, hear, or smell

		existing map. The device will be able to take photos and/or hyperspectral images in order to create a 3D model of the facility, which can be accessed through Virtual Reality (VR) techniques to conduct the facility survey virtually. Remote connectivity allows a user to interact and guide the vehicle for additional close-up capturing. Optional measurement gear may be carried by the vehicle for measurements of thickness, deformations, and/or detection of cracks.	oxygen, presence of toxic gases, and the risk of falling from heights.				mapping that cannot be checked.	the area, which can be important in some surveys.
16	DNV	Inspection: Hull Insights enables operators to perform routine inspections and maintenance targeted on high-risk compartments, evaluation of cumulative fatigue load on structures, and special follow-up after heavy weather.	Hull Insights provides operators with full awareness of their assets' current condition. This insight allows operators to develop standards and ambitions for increased safety and efficiency.	3	3	Hull Insights enables operators to plan ahead and schedule targeted condition-based inspections and maintenance, and it supports fact-based decision making.		As a digital product, potential challenges will include understanding and accommodating user behavior and customer needs. As a data-based product, future development will benefit from an ever-growing collection of data sources.
17	HonuWorx, ORE Catapult	Inspection, Monitoring, Repair: Ridley and Loggerhead will support a range of operations as a submersible delivery craft and mobile power and communications hub of ROVS and AUVs. These technologies are aimed to remove barrier of the RIT industry in terms of cost, carbon footprint, battery life at sea, and digital connectivity.	Ridley and Loggerhead enable the submerged launching of ROVs and AUVs, thereby eliminating risky crane drops associated with manned operations and removing the dependence on large crewed diesel-powered vessels for the deployment of robots. This capability is especially beneficial during heavy weather, during which manned missions may not have been possible and/or would have posed safety risks to personnel.	3	5	Ridley and Loggerhead are poised to disrupt the commercial model of subsea operations. In addition to the associated safety benefits, these technologies allow for supervision and control of the offshore robotic operations to be managed from onshore facilities. Onshore teams are equipped with secure and real-time access and control of operations.	Downtime of mothership technologies may pose challenges to or disrupt the operation of the dependent worker vehicles (ROVs, AUVs).	Users of remote technologies, such as Ridley and Loggerhead, are required to adapt to cutting-edge remote operations centers for remote operations. HonuWorx uses Distributed Control Centers (DCCs) for access to control and mission planning modules.
18	Innvotek, Offshore Renewable Energy (ORE) Catapult (ROBFMS and iFROG projects)	Inspection, Testing, Maintenance: Amphibian supports visual inspection (using HD cameras and high power lights), removal of corrosion, bio-fouling, and unwanted surface coatings (using the high-pressure water jet cleaning module), corrosion mapping (using multichannel Ultrasonic Testing), weld inspection	High-quality data and immediate cleaning of critical infrastructure reduces risk to personnel.	2	5	Amphibian is capable of providing not only visual checks and structural assessments, but also immediate cleaning and maintenance. It also provides unique agility on curved and domed steel structures.		Full software training packages, in addition to technical support for both software and hardware, are provided by Innvotek to aid with the challenges of using advanced NDT methods.

		(using Phased Array Ultrasonic Testing), wall thickness monitoring (using Pulsed Eddy Current Testing).						
19	MarynSol, HydroSurv, Offshore Renewable Energy (ORE) Catapult	Inspection: SeaWynd uses LIDAR (Light Detection and Ranging) and MBES (Multibeam Echosounder) sensors mounted on the USV to generate a high-resolution 3D-georefereced structural mesh of the turbines structure and HD video capabilities to populate the mesh with high quality textures allowing a realistic inspection data model of the turbine. The most recent tests at the Levenmouth Demonstration Turbine demonstrated SeaWynd's ability to generate an up-close, detailed, 3D-georeferenced mesh of the turbine structure and surrounding area.	MarynSol's autonomous vehicles can operate close to assets safely, reducing personnel risks.	2	5	SeaWynd and CableWynd can be combined as the OWynd Offshore Windfarm inspection package offered by MarynSol. Owynd is underpinned by SeaSmart, a sophisticated software package that automates the acquisition, processing and reporting of marine survey data and can work across a variety of autonomous vehicle platforms.		New technologies face the challenge of accessing real-world operational sites for testing and demonstration. Currently, the Catapult Levenmouth Demonstration Turbine provides such facilities to technology developers, reducing time to market.
20	MarynSol, Offshore Wind Industry Council (OWIC)	Inspection: CableWynd combines high-resolution sonar imagery with accurate cable positioning to provide a detailed and efficient inspection of offshore wind farm interconnection and export cables.	MarynSol's autonomous vehicles can operate close to assets safely, reducing personnel risks.	3	5	The OWynd Offshore Windfarm inspection package offered by MarynSol, which includes SeaWynd and CableWynd, is underpinned by SeaSmart, a software package that automates the acquisition, processing and reporting of marine survey data and can work across a variety of autonomous vehicle platforms.		New technologies face the challenge of accessing real-world operational sites for testing and demonstration. Currently, the Catapult Levenmouth Demonstration Turbine provides such facilities to technology developers, reducing time to market.
21	DNV	SMM consists of two independent features, both using ML algorithms to replace physical sensors : 1) *Mooring line failure detection mode*: detects failed/unattached mooring line. 2) *Virtual load sensor mode:* hull movement and acceleration combined with system modeling and ML algorithms accurately determines mooring line tension, and therefore fatigue life. Both elements can be run real time (if there's sufficient bandwidth), or data can be collected periodically and batch-processed.	Early detection of a mooring line failure reduces the likelihood of cascading failures and catastrophic loss of floating foundation mooring. Monitoring mooring line fatigue loads reduces likelihood of a mooring line failure.	4	5	At present, mooring monitoring systems rely on in-situ load sensors, which often fail in the harsh marine environment and are difficult to replace. The SMM system can detect a failed mooring line faster than a load sensor. SMM eliminates the need for physical load sensors BWL, leading to a much more reliable system.	If the hull/vessel position and orientation or the position of each mooring lines is inaccurate, then the digital model will yield erroneous results, leading to incorrect conclusions regarding the state of the mooring lines. This could result in failure to detect a detached mooring line or under- or overestimating fatigue loading.	

List of Acronyms	Definition
AUV	autonomous underwater vehicle
AWL	above water line
BWL	below water line
CTV	Crew Transfer Vessel
HD	High definition
ICCP	Impressed current cathodic protection
IR	Infrared thermography
msw	meters sea water (metric unit of pressure)
OSS	Offshore substation
RIT	Remote inspection technology
ROV	remotely operated vehicle
RT	Remote technology for monitoring inspection, testing, mai
SLAM	Simultaneous localization and mapping
SOV	Service Operations Vessel
USV	Unmanned surface vehicle
UT	Ultrasonic testing
VR	Virtual reality
WROV	Work-class ROV

0	Full manual operation (no autonomy, no RIT)
1	RIT is operated from the WTG nacelle/hub (no blade entry required)
2	RIT is operated from the WTG base platform (no tower climb required)
3	RIT operated from a nearby vessel (no transfer to WTG platform required)
4	RIT is operated from shore, for limited set of scenarios
5	RIT handles all operational decisions with no input from a human at all

DNV

Register 9: Register of **best practices for documenting the results** of remote inspections, maintenance, testing and repair

Explanatory note:

This register presents best practices for acquiring, processing, and summarizing the data and integrating the results into the operator's annual Self-Inspection Report.

BSEE requires that all offshore wind farm operators develop self-inspection programs per 30 CFR 585.824, including an annual Self-Inspection Report

DNV has identified Data Science/data mining/machine learning as the direction RIT data analysis is heading, with the annual Self-Inspection Report as an outcome of the Data Reporting phase.

PART 1: Summarizes critical features of a documentation gathering and management system

PART 2: Lists predictive maintenance programs and tools employing data from remote systems, as well as examples.

For complete workbook, please see **10311530-HOU-XL-01-B RemoteTechnology.xlsx** that accompanies this report.

PART 1: CRITICAL FEATURES OF A DOCUMENTATION GATHERING AND MANAGEMENT SYSTEM

	Term	**Description**	**Minimum information to be included in BSEE Self-Inspection Report**
	Data Science approach	Data science is a field of applied mathematics and statistics that provides useful information based on large amounts of complex data or Big Data. (1) Efficiently using results generated by remote inspection, maintenance, testing, and repair can be challenging as the type and typically large quantity of data may be difficult to integrate into existing reporting systems. Tackling this challenge by mining the data using ML and AI methods as well as standardizing and automating remote inspections reporting is key to successfully integrate new remote technologies to the inspection, maintenance, and repair processes. DNV researched best practices for documenting the remote activities results through discussion with our network of clients, engineers, and field surveyors. It is clear that the principals of Data Science are increasingly being applied to large dataset of all kinds, including those derived from remote inspection, maintenance, testing, and repair.	* A description of which Data Science method was employed to process the remote inspection data
	Data Science work process	The cross-industry standard process (CRISP) for Data Science has six main parts: A) business understanding – understand what problem to solve and why, B) data understanding – get to know your data and how to acquire it, C) data preparation – clean your data and make it fit for purpose, D) modelling – build analytical models from the prepared data, E) evaluation – evaluate carefully whether the model meets the performance and purpose demanded, and F) deployment – deploy the model into a digital solution/interface (data reporting).	

		Note that CRISP is not a linear waterfall process, but an agile process with multiple iterations of exploration and trial-and-error with continuous improvement.	
A	Business understanding	This phase focuses on first understanding, from a business perspective, what the end-user really wants to accomplish, assessing the situation (available resources, project requirements, cost-benefit analysis), determining data-mining goals (technical), and developing a project plan.	* Description of the inspection plan that specifies the AWL and BWL components to be evaluated (both fixed structures as well as floating, including mooring systems), the parameters measured, frequency of measurements, and how the selected Data Science method will facilitate that evaluation * Type(s) of remote inspection(s) employed (see registers for Task 1 and Task 2 for examples of remote inspection methods and commercially available RIT, and Task 8 for RIT under development), and objectives of the RIT campaigns
B	Data collection/acquisition	Collecting the right data in sufficient quantity is a vital first step toward the end-goal of documenting the results of a measurement campaign in a report. Data intended for use in ML or AI algorithms must be fit for purpose. In many cases, the data available is a by-product of the WT control systems and CMS, and not necessarily collected with the goal of informing data-driven models. Further, there must be sufficient data to train data-driven models on what to detect in order for the ML algorithm to interpret important features in the data. Understanding how data will be used/processed needs to inform how it will be collected in the first place.	* Summary of the data collected for the report (e.g., sample frequency, resolution, ML algorithms employed)
C	Data storage/security	Data (and IT infrastructure in general) is increasingly being stored in 'The Cloud' (a collection of remote servers owned by a company), which provides the benefits of flexibility, accessibility, and greater opportunities for collaboration, as well as risks such as increasing aggregated costs as storage requirements grow, lack of interoperability with other cloud-venders, potential for lost data due or compromised system due to cyber attacks.	* Document steps taken to ensure the confidentiality and integrity of all data saved in 'the Cloud' to ensure there is good oversight over the data
	Data handling	Data is an asset that can have tremendous value, and needs to be treated as such. Data handling refers to procedures related to data security, which involves classifying data according to the sensitivity level and how the data must be handled. It is required first to define the sensitivity levels by outlining the scope of what's included as well as examples, and the degree of protection required for data in each level.	
	Data processing	Big data sets can include hundreds of billions of individual data points that are typically stored in thousands of commodity servers, so this data cannot be processed using traditional data analysis, but instead must use parallel processing techniques in order to be efficient. Processing Big Data involves a number of steps that can be grouped as follows: gather data, analyze data, process data, distribute data.	
	Data cleaning	Cleaning data involves removing erroneous data and selecting relevant data. This important step must be carried as part of the data preparation stage. Neglecting this stage could generate an erroneous model during the modelling step.	

	Data quality/resolution	The ISO 8000 standard defines Data Quality as "Data fit for intended use." Intended use must therefore be well defined, in order to derive the required characteristics of the data. This means that data of high quality for one purpose may be deemed poor quality for a different purpose. To assess data quality for a given purpose there must be sufficient metadata (background information) available, and the quality assessment is then done with respect to the requirements for each different use. Faulty data collection (e.g., measurement) will result in useless data, e.g., sensor drift, missing data, noisy data, or not measuring at the right resolution. A verifiable data collection process is a prerequisite for obtaining high-quality data. For example, measurement design, calibration, and test procedures, or metadata checklists etc. are all processes designed to improve data quality.	
D	Machine learning in RIT	Early Artificial Intelligence (AI) focused on building sets of expert rules to imitate intelligent systems such as chess simulators. Machine Learning (ML) is a subset of AI and looks at how rules can be built in an automated way from data. These rules are updated when new data are available. Machine learning, statistics, and data mining all use quite similar techniques, but the emphasis may be on different aspects. Pitfalls to avoid in ML include: using training data as test data; having too little data to properly train; lack of relationship in the data; failing to use the simplest possible model.	* Summary of ML algorithms used to mine the data for information about the condition of the components
	Deep Learning	DL is a subset of ML, where rules are built using deep neural network models.	
	Big Data	While big data is typically characterized by volume, velocity (speed of new data creation), variety (from structured to unstructured), and veracity (accuracy and uncertainty of the data), in practice it's mainly about volume. Big data can run into storage issues due to limitations on storage, memory, and/or computation speed.	
E	Data-driven modeling	The vast amounts of data collected using RIT and combined with increased computer processing power and speed is enabling development of more and more data-driven models. Models are being derived from patterns and signals found in the data, rather than based on assumptions about physical behavior. Data-driven models are enabling detection of anomalies at an earlier stage, which influences maintenance plans and repair campaigns, and saves operators money.	* Summary of the overall structural condition of each inspected component as evaluated using data-driven modeling, for components
F	Data reporting	Summarizing the output from data-driven ML models that have been trained on large datasets to identify anomalies in the measured data that can then be used to inform predictive maintenance programs is the ultimate objective of CRISP. All previous steps in the data science work process must be successfully completed to achieve this goal.	* Report of what repairs were identified as being needed for each component inspected * Assessment of the overall structural condition of the components
	Predictive Maintenance	Data science and predictive analytics are used to estimate when a piece of equipment might fail so that corrective maintenance may be scheduled prior to catastrophic failure. This enables scheduling maintenance at the most convenient and cost-effective time, optimizing the component lifetime but avoiding	

PART 2: PREDICTIVE MAINTENANCE PROGRAMS/TOOLS EMPLOYING DATA FROM REMOTE SYSTEMS AND EXAMPLES

	Feature	Description	Industry status	Notes
1	SkySpecs	Uses AI-based fault detection technology that enables detection of anomalies or damage earlier than other inspection methods. Their CSM software connects to any vibration or SCADA sensor data stream, and since the AI is trained on a	Fully automated drone plus CMS; in commercial operation	SkySpecs reports that in 2021 their team carried out 25 onshore turbine inspections in one day using their fully automated drone

		large library of data for known failures, it's able to detect faults more accurately than non AI-based CMS systems. SkySpecs has developed the capability to integrate the processed data into work order systems, such as the annual Self-Inspection Report required by BSEE.		technology. Previously it required a technician an entire work day to inspect one turbine using rope access.
2	Aerodyne	DT[3] -- AI driven defect detection. Reporting and analytics provide detailed information on the blades. * Blade experts use high-resolution data to perform remote inspection on 3D desktop application developed in-house. * Data resolution up to 1mm/pixel provides sufficient quality for defect marking * Eliminates need for rope access, lifts or cranes for inspection * Improved efficiency of reporting (automated)	Aerodyne has inspected over 24,000 wind turbines (mostly onshore).	Aerodyne reports operation cost savings of 35%, and 50% cos saving in defect marking and categorization.
3	VERISTAR AIM 3D (BV)	BV's asset integrity management (AIM) combines a 3D digital twin of any offshore asset (e.g., floating WTG substructure) with remotely collected data in a collaborative software platform that supports risk based inspection and condition based maintenance approaches. The process involves risk assessment that identifies critical plant components and their failure modes; defines performance standards; develops and implements inspection, maintenance and audit programs; and provides live status reports, interpretation and feedback to improve the asset management. Ideally, the 3D digital twin models are developed before construction, during the design stage, and then used through an asset's life, providing a single source of truth for better decision making about the asset's actual and future condition.	Commercially available. Application: vessels, offshore fixed or floating infrastructure	Accumulated data through the life of the assets should enable a combination of predictive responses to guide maintenance planning as well as feed back into better designs.
4	Nerves of Steel (DNV)	DNV's 'Nerves of Steel' hybrid digital twin tool for vessels and floating structures uses digital analytics and modelling to monitor an asset's hull structure during operation. The underlying concept uses various data sets (external environmental data or local sensor data) combined with digital models of the asset to develop a hybrid replica model of the vessel's structure. This can be used in real-time to monitor the asset's condition and plan targeted and cost-efficient maintenance and inspection activities. Hybrid twin technology uses a combination of numerical design models and data from actively recorded strain gauge sensors on board the floating structure. These sensors allow for a full understanding of the accumulative loading and current state of the structure. The technology blends computer-simulated modelling with real-time data, which is then streamed to the operator via a data transfer solution.	Pilot projects. Application: vessels, floating structures	DNV's online visual dashboard presents data to the operator on stresses in the asset's structure, alongside information that can be used to identify areas at higher risk of cracks or deformities. The information, which is constantly recorded, can be accessed and analyzed to inform decision-making and implement inspection based on risk priority.
5	WindGEMINI (DNV)	DNV's digital twin online tool providing information into turbine conditions and performance and enabling better-informed wind operation decisions. Operational benefits and applications include: * A turbine life estimator that uses aeroelastic modelling to estimate the effect of site conditions on the fatigue accumulation of the main structural components. It provides an estimate of the remaining life of a turbine which can be used to identify opportunities to extend life or upgrade turbines.	Commercially available. Application: Wind farms. Has been implemented in more than 33 wind farms	WindGEMINI has been used to detect structural anomalies, such as a blade crack that was identified when the Structural Integrity Monitor highlighted a high level of 1P activity at one of the turbines, triggering a blade root inspection that revealed a crack at the blade root. Replacing the blade took two days. Had the crack gone undetected the blade might have

		* Predictive analysis of the turbine drivetrain identifies patterns indicative of incipient failure modes and raises alerts with varying confidence levels. This information can be used by owners and operators to avoid failures, optimize inspections and reduce downtime. This feature can accept data collected via remote monitoring, inspection, or testing. * A power curve performance watchdog identifies shifts in the turbine power curves and sub-optimal control modes, so that they can be corrected to regain any potential energy losses. * Structural integrity monitoring uses high-frequency data to identify issues, such as rotor imbalance and foundation degradation, which can have adverse effects on energy capture and turbine life.		eventually failed catastrophically and taken up to two weeks to repair, causing significant lost energy revenue.
	IRIS Data Platform (InterSystems)	InterSystem's IRIS Data Platform provides database management, interoperability, and analytics capabilities to data-intensive applications, and integrates into existing infrastructure. It brings all data (from any source) together with real-time monitoring and real-time tracing solutions to aggregate, normalize/clean, duplicate/backup, process and transform the information into the reporting that's needed. * Interoperability with diverse technologies. Capable of aggregating data from multiple sources (flat files, Excel spreadsheets, CRV files, data logger output, etc.), delivering raw data to application in the required format for processing by existing functions (including AI and ML algorithms), transferring processed data to where it needs to go, including to standardized reporting template. * IRIS platform can connect to cloud-based systems, on-premises, or hybrid * Capable of scaling: can process incoming data at high ingest rates while simultaneously executing analytics on the incoming data and large data sets. One customer processes multiple billions of transactions every 24 hours. * Creates data flow history, tracking the process through which data is moved and acted upon; e.g., if the power went down, the IRIS platform can restart from th4e point where data transfer or data processing stopped	Commercially available since 1978. Application: Industry-agnostic, but major customers include Healthcare, Banking, Energy Industry	The IRIS Data Platform represents an example of a data processing and analysis system that can manage multiple data streams from RBI systems using RT for offshore wind farm maintenance. It is an application of Data Science that fills gaps in existing processes and provides the needed functionality to produce output in the format required. WS Trends, a software developer in the Czech Republic, has used InterSystems solutions to build an application for managing energy grids that provides added capabilities for both consumers and producers.
6	EXAMPLE: (DNV) Automated characterization of the operational state of wind turbines	Wind turbines generate energy and in the process also produce vast quantities of operational data. Methods for mining this data for valuable insights on the operational state of the wind turbines are under development. For this Data Science application, DNV developed ML algorithms specifically to classify the turbine operating state into normal and derated modes. The turbine data were distributed among a cluster of machines, and the ML model, after being trained using a separate training dataset, was distributed to all nodes in the cluster, facilitating parallel processing of the data to quickly classify the various operational modes. The model required about 13 mins to train, and 0.1 sec to run. It correctly predicted derating 82% of the time, and normal operation 97% of the time. In addition, the ML method captured a number of conditions that had been mislabeled by the existing manual methodology. When subsequently implementing the ML model into the service, a downscaled	Early commercialization for onshore wind turbines	This example indicates that the ML model could be used for automatic flagging of a specified turbine operating condition, considerably reducing the time needed by a wind analyst for manual flagging. Note that the model was trained using data that was manually flagged by an expert. A more advanced approach would be to use unsupervised learning using data directly from wind turbines to build a ML model. This would require more development time as well as deeper involvement of wind experts to confirm accuracy of the resulting model. Results from this ML model were automatically

		version was required, as the service was based on a standalone PC solution. This is likely to be the case for most currently operating projects, as it will likely take years for the industry to adopt the IT architecture needed to implement the Big Data version.		generated to meet the requirements of the customer.
7	EXAMPLE: (DNV) Prediction of remaining useful life of a fleet of gas turbines due to thermo-mechanical fatigue failure	Similar to wind turbines, gas turbines are typically equipped with CMS measuring conditions such as temperature, pressure and vibration in various parts of the turbine in real time. CMs can identify significant changes in system parameters that could indicate a fault developing., which information may then be used to schedule maintenance or plan some other preventive actions. Expanding existing CMS and control systems to incorporate data-driven models developed by data analytics and ML can be used to estimate the remaining useful life of the gas turbine.	Under development for gas turbines	This research example applies specifically to gas turbine blades affected by thermo-mechanical fatigue, but the principle is applicable both to other types of data (such as vibration or pressure) as well as to different types of components (such as wind turbine blades, generators or gearboxes). The prediction of remaining useful life is a highly sought service by wind farm operators trying to maximize the utility of their wind farms.

Acronyms	
3D	3-dimensional
AI	artificial intelligence
AWL	Above water line
BWL	Below water line
CMS	Condition monitoring system
CRISP	cross-industry standard process
ML	machine learning
SCADA	Supervisory control and data acquisition system
WT	wind turbine

TRL Definitions

Definition Of Technology Readiness Levels

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

APPENDIX B – LIST OF COMPANIES

The following companies were interviewed, surveyed and/or researched during the course of this study. This list represents a representative selection of companies focused on remote technology actively targeted for the offshore wind market or that has potential applications for offshore wind inspection, maintenance, testing, or repairs. Companies are listed in alphabetical order.

#	Company	Application
1	4Subsea	Below water
2	ABJ	Above water, service provider
3	Aerodyne Measure	Above water, service provider
4	ANYbotics	Above water
5	Apellix	Above water, service provider
6	Applus	Below water
7	BAE Systems	Below water
8	Blade Edge	Above water, service provider
9	Bladebug	Above water
10	Boston Dynamics	Above water
11	CWIND / Global Marine	Below water
12	DJI	Above water, Below water
13	DNV	Above water
14	Drone Base	Above water, service provider
15	ECA Group	Below water
16	Ecosub	Below water
17	EddyFi Technologies	Above water, Below water
18	EM&I	Below water
19	Fraunhofer IWES	Above water
20	General Dynamics	Below water
21	Houston Mechatronics	Below water
22	Hydroid/Huntington Ingalls	Below water
23	Innovate UK	Above water
24	Innovtek	Below water
25	International Submarine Engineering, LTD, (ISE)	Below water
26	ISE	Below water
27	Kawasaki Heavy Industries	Below water
28	Konsberg	Below water
29	L3 Harris	Below water

30	MarineSitu	Above water
31	MarynSol	Below water
32	Mitsubishi	Above water
33	Oceaneering International, Inc.	Below water
34	Olis Robotics	Above water
35	ORE Catapult	Below water
36	Perceptual Robotics	Above water
37	Pharos Offshore Group	Below water
38	Precision Hawk	Above water, service provider
39	Rope Robotics	Above water
40	SAAB	Below water
41	Saipem	Below water
42	Sandia National Labs	Above water
43	SIMS Offshore	Below water
44	Sky Specs	Above water, service provider
45	Skyguage Robotics	Above water
46	Skyline Drone	Above water, service provider
47	Subsea7	Below water
48	Superdroid Robots	Above water
49	Teledyne	Below water
50	V2subsea	Below water
51	Vaarst (technology wing of Rovco)	Below water
52	Wind Power Lab	Above water, service provider
53	Xocean	Above water

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