Technology Drivers in Windfarm Asset Management

Position Paper

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Executive Summary

The Opportunity

As part of the UK’s programme for a sustainable, low-carbon future, increasing use will be made of wind energy. Presently the UK has 5 GW of wind energy, enough to power about 3 million homes. The capital investment required for this US offshore infrastructure could be as much as £120 billion. Operation and Maintenance (O&M) in the UK could be an industry worth as much as £2 billion per year by 2025. With the UK being a world leader in offshore engineering, this presents huge potential for UK industry to establish itself, become leading exporter of services in this field and support 60,000 direct and indirect jobs.

The Technical Challenges

Skills shortage exists in many of these areas. Present industry practice in the sector is good, though there is substantial opportunity to adopt best practice from other sectors, particularly the offshore oil and gas industry. Present data-driven condition monitoring solutions are limited by their inability to effectively sense key operational parameters at all key points. There is thus a need to investigate alternative technologies.

Predictive Maintenance can be divided into data-driven (sensing the state of equipment directly) or model-driven (using knowledge of the equipment to predict how it will age). Both are needed to improve reliability and efficiency.

The opportunity for the UK industry to establish itself becomes leading exporter of services in this field and support 60,000 direct and indirect jobs.


New, high fidelity sensing technologies are becoming available. However, these still have to be fully tested on representative systems and integrated into methods that allow accurate diagnosis of degradation. For example, power electronic systems are a major cause of equipment downtime. The extended use of these systems in a harsh offshore environment has been identified as insidious for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities. The extended use of RAS systems in a harsh offshore environment has been identified as insidious for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities. The extended use of RAS systems in a harsh offshore environment has been identified as insidious for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities.

Remote Operated Vehicles (ROVs) or Robotics and Autonomous Systems (RAS) in the 2014 innovation UK RAS Strategy identified offshore energy as an area where the UK could take a global leadership role. For subsea systems, the seabed presents a complex environment where existing modelling and testing has been identified as insufficient for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities. The extended use of RAS systems in a harsh offshore environment has been identified as insidious for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities. The extended use of RAS systems in a harsh offshore environment has been identified as insidious for future challenges. Opportunities exist for RAS systems with increased and new sensing capabilities.
The use of modelling is particularly important for future wind farms which use techniques not widely trialled (for example floating wind turbines). Assessing potential problems before a large investment is made is thus important both for getting best value from whole system capital expenditure (CAPEX) and operational expenditure (OPEX). While a number of key technical challenges clearly exist, the reliability of communication infrastructure is enabling this data flow and delivers sufficient information. However, an upgrade of present telecommunication infrastructure may need an upgrade of present telecommunication infrastructure. This in turn will increase work in this area has been limited. There is a clear opportunity here, machine learning approaches have a clear opportunity here, person time and capability to effectively diagnose problems. Which data is particularly useful, because of lack of skilled workers existing data, substantial improvements could be made. However, even to be augmented for best practice solution. It is particularly important to establish short-term driving factors, not just the long-term averages which are typically quoted, as well as the effects of data uncertainty, as well as the effects of data uncertainty, as well as the effects of data uncertainty, as well as the effects of data uncertainty.

The condition monitoring data presently generate needs to be augmented for best practice solution. However, even with existing data, substantial improvements could be made. Much data is presently unused, because of lack of skilled workers existing data, substantial improvements could be made. However, even to be augmented for best practice solution. It is particularly important to establish short-term driving factors, not just the long-term averages which are typically quoted, as well as the effects of data uncertainty, as well as the effects of data uncertainty, as well as the effects of data uncertainty, as well as the effects of data uncertainty.

While a number of key technical challenges clearly exist, the potential for the economy, for job creation and for a world-leading position in a rapidly increasing global market is evident. The condition monitoring data is particularly important for future wind farms which use techniques not widely trialled (for example floating wind turbines). Assessing potential problems before a large investment is made is thus important both for getting best value from whole system capital expenditure (CAPEX) and operational expenditure (OPEX).
2. Introduction

A key challenge for the UK in the 21st Century is securing a sustainable low-carbon energy supply. This challenge requires a substantial change to the UK electrical energy generation mix. In this mix, low-carbon renewable energy generation, as a substantial change to the UK electrical energy supply, is crucial.

Operation and Maintenance (O&M) cost has been estimated at a quarter of the total cost of an offshore installation \[2\] i.e. as much as £40 billion for future UK offshore wind. This cost is expected to rise as sites move further offshore. Such sites, Fig. 1, are 100 km or more offshore in the North and move further offshore as sites that will grow generation will mainly be wind energy at sites that will grow generation. According to the Crown Estate \[4\]: 'Based on the UK Government’s projections for the deployment of offshore wind power, the O&M of more than 5,500 offshore turbines could be worth almost £2 billion per annum by 2025 — an industry similar in size to the UK passenger aircraft service business.'
In common with best practice in other sectors, the long term industry vision for the offshore renewable energy sector is advanced predictive maintenance, based on data driven approaches, using improved sensing and digital models that can accurately forecast the future state of health and therefore maintenance requirements of these complex assets. 

Furthermore, challenges in remote accessibility, an aging workforce and hazardous environment working at sea drive a trend for robotic enabled autonomy which will coordinate with the improved advanced sensing. These robotic systems will be coordinated via centralised onshore operating systems and will be driven by advanced data analytics. Increasingly the security of future supply will be enabled by data, not metal.

3. State of the Art

The present state of the art of Operation and Maintenance (O&M) Offshore Wind refers to activity following commissioning which is undertaken to ensure safe and economic operation of the asset, achieving an optimal balance of running cost and electricity production over the asset life (typically 20-25 years). While the sector is similar to Inspection, Repairs and Maintenance (IRM) in the onshore oil and gas sector, standardised practices have not yet emerged, and cost pressures are far greater.

The present state of the art, particularly offshore, will be enabled by data, not metal. O&M activity includes management and administration functions as well as the high level control and remote monitoring of the asset. These are continuous on-going activities, typically based onshore.

Taking the two distinct parts of this in turn:

and cost pressures are far greater.

and gas sector, standardised practices have not yet emerged, inspection, repairs and maintenance (IRM) in the offshore oil industry, especially offshore wind. While the sector is similar to asset life (typically 20-25 years). While the sector is similar to the crown estate ([4], offshore wind O&M refers to activity following commissioning which is undertaken to ensure safe and economic operation of the asset, achieving an optimal balance of running cost and electricity production over the asset life (typically 20-25 years).

Offshore wind O&M remains similar to that outlined in GL Garrad Hassan’s definitive 2013 summary for Scottish Enterprise and the Crown Estate ([4]).

4. Breakdown of cost of energy for a typical UK project with first generation in 2020, from data in [7].

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Share</th>
</tr>
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<tbody>
<tr>
<td>Project</td>
<td>15%</td>
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<td>17%</td>
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<td>Turbine</td>
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<td>12%</td>
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<tr>
<td>Installation</td>
<td>5%</td>
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<tr>
<td>Transmission</td>
<td>4%</td>
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<tr>
<td>Cost of Capital</td>
<td>4%</td>
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Fig. 3: Traditional O&M Overview for Offshore Windfarms
Maintenance refers to periodic interventions in order to facilitate the repair and upkeep of the asset. Maintenance accounts for the majority of O&M costs. Maintenance can be further subdivided.

Preventative maintenance refers to proactive repair and replacement of assets and includes surveys and inspections and is typically scheduled periodically in advance. This can further be divided into Data Driven methods, in effect the degradation monitoring of key attributes; and Model Based methods in which environmental stresses rather than equipment attributes are monitored, and their effects inferred in order to determine health.

Corrective maintenance refers to the replacement of failed or damaged components and is typically scheduled in reaction to a detection trigger. An important goal of modern O&M is identifying reliable early triggers so that maintenance can be undertaken when the required intervention is still inexpensive and undertaken when the required intervention is still expedient before significant equipment degradation is detected. An important goal of modern O&M is to achieve a safe operation of the asset, increasing the amount of power generated and reducing the costs of running the asset. Maintenance contracts are typically held between the project owner and the Offshore Transmission Owner (OFTO). Wind turbines are normally maintained by the Original Equipment Manufacturer (OEM) and submarine cable array maintenance by the Original Equipment Manufacturer (OEM). Wind turbines are normally maintained by the OEM and the Offshore Transmission Owner (OFTO). Wind turbines are typically maintained by the OEM and the Offshore Transmission Owner (OFTO).

Maintenance is strongly constrained by safe access. Access is limited in terms of transit time to site and accessibility of the site to maintenance crews (for example during bad weather). A combination of workboats, helicopters and offshore accommodation may be used to ensure accessibility, with combinations of access resulting in different cost-breakdowns. If systems are specifically designed as Line-Replaceable Units (LRUs), i.e., pieces of equipment in sockets, preventative units (LRUs) can be replaced or replaced in reactors. In addition, monitoring and repair of equipment is typically subject to a warranty period. Throughout the project, the warranty period should be underpinned by the Warranty Agreement, which can provide guarantees for the first few years of their life.

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models would generate a lot of potential interventions — which
are repeated within each year. However, it is also because such
complexity of the models required and the range of expertise
was limited, which is to a large extent because of the
stronger focus on efficiency. This task is time consuming unless a
modern system is available. There is also
efficient. This task is time consuming unless a modern system
and performance norms. During this maintenance
critical and performance norms. Traditionally, maintenance is
and predictive maintenance. Traditionally, maintenance is
including methods such as scheduled, on-condition monitoring,
and targeted interventions and preventative maintenance to
about targeted interventions and preventative maintenance to
reduce the initial failure rate and initial period warranties are
reducible. Hence other metrics are often used such as the
energy availability.

4. Research to Date

Traditionally, research into asset reliability and availability has
been focused on stress and strength analysis. Stress refers to
stress and strength analysis. Stress refers to stresses which
affect the remaining usable life. Strength refers to the ability of
the asset to withstand stresses. Strength refers to design
research into stress and strength analysis. Stress...
would need sorting, prioritising and could lead to considerable expense if technicians needed to be dispatched every time a potential problem is flagged. As it is, a medium-sized wind farm already generates 100+ alarms at any time, many of which have had to be ignored due to lack of safe, cost-effective intervention options.

The value of R&D in recent years is evident: best practice has improved so that now 85% of alarms are resettable remotely.

A key element is better use of measurement feedback – i.e. not just the compilation of failure and reliable statistics for preventative maintenance, but also the use of reliable prognostic techniques which allow targeted interventions. Combined stress and strength models, with condition monitoring solutions, AI and robotics monitoring (real time data) can therefore present an important advance, but is something that is only starting to become feasible.

The HOME Offshore project accordingly aims to address this challenge by bringing together expertise from a number of areas. It builds on successful projects in wind farm and connection to shore reliability (EPSRC Supergen Wind D034566/1, Supergen Wind 2 H018662/1, Supergen Wind Hub D034966/1, Supergen Wind 2 H018662/1), and in power electronics reliability (EPSRC Multi-terminal HVDC Networks L01401/1, EPSRC Multi-terminal HVDC Networks L01401/1, EPSRC Renewable Wind 2 H018662/1, Supergen Wind Hub D034966/1, Supergen Wind 2 H018662/1, Supergen Wind Hub D034966/1, Supergen Wind 2 H018662/1).

It also complements international hardware demonstrator projects (e.g. EU BEST PATHS) and planning research (e.g. EU Highway 2050, REALISEGRID, IRENE40).

It aims to utilise a number of disruptive technologies have emerged in recent years to provide a significant improvement to offshore O&M.

Game Changers:

1. Offshore O&M is undertaken remotely, which taken together can provide a significant improvement to offshore operations, which can be managed using computer models with condition monitoring solutions, AI and robotics monitoring (real time data) can therefore present an important advance, but is something that is only starting to become feasible.

2. The goal needs to be the use of reliable diagnostic techniques which allow targeted interventions.

3. Advanced sensing techniques have become affordable and with the required mission duration and support available to allow remote initial inspection and support.

4. Drones of the required sophistication, controllability and multi-physics strength-stress models are still extremely challenging to develop, which allow targeted interventions.

5. Data analytics has advanced to the point where the typically large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriately large volumes of data generated can be appropriate...
Integrating these into a framework to improve the traditional maintenance cycle has the potential to further significantly reduce costs, Fig. 4.

The following pages summarise the state of the art in specific autonomous systems (e.g. robots) self-certification.

Fig. 4 Future maintenance cycle with supplementary features.
data, though remaining a challenge at present. The problem remains evaluating operation options on reliability and diagnosing fault physics events, and allows the user to run what-if scenarios to optimize the system.

By combining these within a package which can model multi-physical windfarms, the challenge within the reliability modeling of offshore windfarms is addressed along with multi-rate simulations, have the potential to address the problem of modeling a larger number of events. Standard models have been formulated for each type of offshore windfarms for offshore windfarms. However, large numbers of small errors can also cause large compound errors. Traditionally, electrical models are used to analyze the operation and planning of transmission and distribution systems. However, strength, stress, and reliability models for offshore windfarms need to be able to accommodate all these factors. This is a challenge that remains a challenge at present.

Fig. 5: Timescales of windfarms events

- Electronics
- Electromagnetic
- Mechanical
- Thermal
- Reliability/Other
1.2 Prior Art Research

Even the most advanced electrical power network simulation packages are principally electrical system simulators. Reliability tools tend to be added as an afterthought, mainly because to achieve a reasonable resolution of results, a simulation time-step 10 to 100 times faster than the smallest event of interest is used. This means, in essence, the number of variables must be checked against every other variable, as well as the number of evaluations scales with the number of variables squared. The actual situation may be better, since sparse techniques may be used (not every variable releases particularly strongly to every other variable) and sparsity techniques may be used, but the general situation may be better since sparsity techniques may be used, since sparsity techniques may be used for reliability tools. Even with sparse techniques, a large amount of computational work is required to achieve this for all study types has not been reported.

Some progress is being made in this field. For example, a multi-physics electromagnetic / thermal model of a wind turbine was proposed in [13] by Lei et al., using a lumped model of the turbine to represent the aerogenerator. In particular, the practice of representing a model with a lumped model of the turbine to represent an aerogenerator is widespread. This approach is also used in the field of electromagnetism, where the thermal model used is also reduced to the real-time system. The thermal model used is also used to reduce the computational time required for the simulation, which is rather slow. 

The software tools used for reliability tools tend to be added as an afterthought, mainly because to achieve a reasonable resolution of results, a simulation time-step 10 to 100 times faster than the smallest event of interest is used. This means, in essence, the number of variables must be checked against every other variable, as well as the number of evaluations scales with the number of variables squared. The actual situation may be better, since sparse techniques may be used, since sparsity techniques may be used, since sparsity techniques may be used for reliability tools. Even with sparse techniques, a large amount of computational work is required to achieve this for all study types has not been reported.

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4.2 Offshore Mechanical System Modelling

4.2.1 General Background

The highly multidisciplinary nature of the physical phenomena occurring in an offshore wind farm have so far prevented the development of a truly whole-farm model of dynamics, capable of simulating all complex interactions.

The ultimate objective is not to maximise the energy produced, but to minimise its cost for a given amount of energy. The difficulty here is that the more energy is extracted, the higher the loads acting on the wind turbine will be, i.e. more expensive components. Therefore, an optimum trade-off should be reached, optimising the energy-to-cost ratio.

The typical uses of these codes are twofold. The first is to optimise the layout of a future wind farm during the design phase: by optimally locating the wind turbines relatively to each other, the total energy produced can be maximised. However, the ultimate objective is not to maximise the energy produced, but to minimise its cost for a given amount of energy. The difficulty here is that the more energy is extracted, the higher the loads acting on the wind turbine will be, i.e. more expensive components. Therefore, an optimum trade-off should be reached, optimising the energy-to-cost ratio.

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2.2 Prior Art Research

Wind farm level models of dynamics have focused mainly on aerodynamics, and can be divided into three modelling scales:

- **Mesoscale**
  - In the HOME offshore project, a holistic advanced AHSE-DEM approach, will be expanded toward the representation of the whole wind farm, supporting the whole system prognostic and diagnostic O&M approach.

- **Plant array scale**
  - Models of dynamics (25, 26) have been widely used for early-stage dynamics (27, 28). The current trend is to represent the undisturbed wind ambient conditions, with high-fidelity CFD codes (generally LES) using less computational intensive CFD codes (29).

- **Wind turbine scale**
  - For aerodynamics, actuator disc models have been widely employed for wind farm control strategy development, giving satisfactory results when estimating the power and analyzing aerodynamics. However, since there is no aerodynamic interaction of single blades, the actuator disc models are used instead when the aim is to reduce the loads on the blades.

**Fig. 6 Modeling scales of a wind farm system**

At plant array scale, Dynamic Wake Meandering (DWM) models can be used, depending on the specific aims. The DWM models are able to capture the wake-deficit evolution and the wake meandering (27, 28). The DWM model is contrasted to the standwind model, and the added turbulence effects are significant to represent the far-wake dynamics. In models can stochastically represent the far-wake dynamics. At the wind turbine scale, Dynamic Wake Meandering (DWM) is an effective tool to represent the wake interactions, wake mixing, and the wind field affected by wake patterns and seederodynamics.
Fig. 7: Physical phenomena and modelling of offshore wind turbine systems, adapted from [25].
Reliability Modelling

4.3.1 General Background

Offshore wind farm reliability (including both turbines and underlying infrastructure) can be evaluated using standard metrics such as availability and capacity factor. Availability may be defined as the ratio of time for which the wind farm operates without problems. This provides a proxy measure of overall reliability and can be defined for the turbines as well as the array as a whole, under the assumption that all turbines operate at the same availability. The main limiting factor in research, however, is the need to capture the underlying short-term operational indicators and their impact on performance. The average availability of offshore wind turbines is growing steadily with recent technological advancements in turbine technology. Meanwhile, offshore grid connections have been enjoying their highest availability in decades.

Notwithstanding such high rates, the availability index does not give a full picture of wind farm performance. Daily or seasonal wind variations on performance, for example, are not clearly indicated in long-term averages which are not sufficient to characterize short-term driving factors. The main limiting factor in research, however, is the need to capture the underlying short-term operational indicators and their impact on performance. The average availability of offshore wind turbines is growing steadily with recent technological advancements in turbine technology. Meanwhile, offshore grid connections have been enjoying their highest availability in decades.

Alternate reliability is the ratio of energy production to the theoretical maximum production. Alternate reliability is widely used in technical reports to evaluate wind farm performance but, like availability, only provides a partial indicator. The reason for focusing on energy production metrics is that availability is a crucial factor driving wind farm operational costs. Typically, the majority of the overall cost of offshore wind energy is carried by initial capital investment (CAPEX) and operational expenditure (OPEX) incurred, whereas the majority of the overall cost of wind farm operations is driven by regular maintenance and repair costs, including operational costs. The reason for focusing on energy production metrics is that availability is a crucial factor driving wind farm operational costs. Typically, the majority of the overall cost of offshore wind energy is carried by initial capital investment (CAPEX) and operational expenditure (OPEX). The main limiting factor in research, however, is the need to capture the underlying short-term operational indicators and their impact on performance. The average availability of offshore wind turbines is growing steadily with recent technological advancements in turbine technology. Meanwhile, offshore grid connections have been enjoying their highest availability in decades.

Accurate estimation of wind farm OPEX is only possible by proper evaluation of short-term operational indicators and their underlying uncertainties. The main limiting factor in research, however, is the need to capture the underlying short-term operational indicators and their impact on performance. The average availability of offshore wind turbines is growing steadily with recent technological advancements in turbine technology. Meanwhile, offshore grid connections have been enjoying their highest availability in decades.
Prior Art

Research

The state-of-the-art in this area is represented by specific operation and maintenance (O&M) simulation software programs based on reliability data. An example is the MATLAB® simulation software (ROSM) which can be used to simulate the hypothetical large, far-offshore wind farm offshore connection (driver by random failure-repair cycles) and include all states and their transition probabilities. The simulation models the reliability of the equipment and the whole system over time. The Monte Carlo simulation is used to estimate the performance of the wind farm and the offshore connection.

In general, the state transitions for individual turbine components (i.e., transitions from a healthy to a failed state) can be assumed to follow a standard Birth-Death Markov process. For a two-state process, the limiting state probabilities are basically the availability (and unavailability) of the component and by extension the turbine itself. By incorporating the turbine model within a time-sequential Monte Carlo simulation, a time-series trace of the wind turbine operation can be simulated over time, with the probability of the wind farm performing correctly.

The EU FP7 ReliaWiND project provided a detailed simulation tool to simulate a particular wind farm. This type of simulation tool can then be used to simulate test cases for example a large offshore wind farm placed at Dogger Bank with a variety of vessel-based and platform-based maintenance routines and find an optimal O&M regime for the farm. Existing studies [31] show that simply changing the topology of the wind farm offshore grid connection can easily improve the availability and energy production indices up or down.

Existing studies [32] show that simply changing the topology of the wind farm offshore grid connection can easily improve the availability and energy production indices up or down. However, in real life, data is not consistently available at all levels of granularity. Modelling assumptions must be extended to account for different levels of precision. Extended simulations generally rely on data from other offshore wind farms, so simulations must account for unknown variables (such as doubly-fed converters) and can only be conducted at a high level of abstraction. The simulation assumptions and underpinning uncertainty are highly sensitive to the input data, and the findings of such maintenance routines [30] are highly sensitive to the input data. However, the findings of such maintenance routines [30] can then be used to simulate the operation and performance of the wind farm.
4.4.1 General Background

The hazardous nature of the operational environments they reside in requires a different set of challenges due to the assets present a different set of challenges. Each of these cables: wind turbines and the HVDC substations. Each of these three sets of assets have been identified which would benefit from the deployment of robotic platforms: subsea.

Three scenarios have been identified which would

- Autonomous offshore energy field, operated, inspected and
- Remote, human interventions.
- Remove, human interventions.
- Using traditional CM methods, by humans.
- Monitoring of assets which are currently inaccessible.
- Targeted mobile sensing in support of existing CM.
- Where RAS technology could be utilised in offshore O&M.

Three scenarios have been identified by the HOME project:

1. Targeted mobile sensing in support of existing CM.
2. Monitoring of assets which are currently inaccessible.

For the scale of the proposed future windfarms, move towards a fully offshore renewable energy sector to enable cheaper, safer and more efficient working practices and move towards a fully autonomous remote inspection. Initially requiring a team of skilled employees to perform the inspection, whilst the inspection of subsea elements (LVs) have been used for remote inspection. For autonomous offshore energy fields, operated, inspected and

4.4.2 Prior Art Research

As discussed in section 4.4.3, required for autonomous remote inspection to remove need for personnel on site to direct and manage vehicle systems and

- Reliable remote inspection. Especially requiring a team of skilled employees to perform the inspection. While either requiring a team of skilled employees to perform the inspection. While using traditional CM methods, by humans.
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For the scale of the proposed future windfarms, move towards a fully autonomous offshore energy field, operated, inspected and

General Background
offshore wind turbines [39]. The current state-of-the-art in sub-

- aerial Platforms

Subsea Platforms

- aerial Platforms

- aerial Platforms

Subsea Platforms

Subsea Platforms
Due to the challenges in obtaining real-time visualisation of data from sensors such as optical and thermal cameras, and various gas sampling technologies, more complex surveys use drones with high capacity onboard storage to collect large amounts of data which is later post-processed. Example applications include digital elevation modelling and ortho-corrected mapping. For visualisation of data from sensors such as optical and thermal camera feeds, 20 kg commercially operated drones provide real-time visualisation of data.
The voltage inside the HVDC converter can reach high values (+/-400 kV), and the valve halls can be subjected to lightning strikes. The inspection robot therefore has to be proven to be resistant to arcing from either the valves themselves or from external sources, and to the significant electric field the operational hall will generate, which may have a detrimental effect on the control components.

These effects need to be understood and mitigated. Traditional solutions are 1) Faraday Cage shielding, which implies covering the whole robot body with a conducting material; 2) Insulation, which implies that part of the robot or the whole robot is made of insulating material.

Given the operational requirements and size constraints, there are also more traditional challenges to overcome. The valve hall will be a GPS denied environment with limited or no lighting, so navigation will likely be more reliant on LiDAR localisation-based methods.

In addition to the electromagnetic considerations, there are also more traditional challenges to overcome. The valve hall will be a GPS denied environment with limited or no lighting, so navigation will likely be more reliant on LiDAR localisation-based methods.

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A combination of simulation and experimental work will be conducted to ascertain the most suitable solution.

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The International Federation of Robotics' annual report estimates the total number of inspection robots sold globally to be approximately 3,600 by the year 2019, which would only cover a third of all existing UK wind farms planned, with 2019 [47]. The use of fixed-point condition monitoring is less than existing methods of deploying robotic platforms is less than existing methods of deploying robotic platforms. A key aspect of making robots cost-effective is ensuring there is a sustainable supply chain. In the field of mobile robotics, this does not yet exist, and the support of the government developing this is crucial to the UK becoming a world leader in this sector.

The assumption made in this initial analysis is that the cost of deploying robotic platforms is less than existing methods or the use of fixed-point condition monitoring. A key aspect of making robots cost-effective is ensuring there is a sustainable supply chain. In the field of mobile robotics, this does not yet exist, and the support of the government developing this is crucial to the UK becoming a world leader in this sector.

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To provide some context, the International Federation of Robotics' annual report estimates the total number of robotic platforms sold globally to be approximately 3,600 by the year 2019. The use of fixed-point condition monitoring is less than existing methods of deploying robotic platforms.
Fig. 10 Forecast of robotic technology for operation and maintenance of offshore wind turbines
The drive train is at the core of the modern wind turbine system. It typically comprises a series of integrated mechanical and electrical components: the shaft, the main bearings and an electric generator with or without a multi-stage gearbox. The current trends in drive train design of the next generation of offshore wind turbines (rated power greater than 7 MW) are dominated by the use of fully rated permanent magnet generators in either low-speed direct-drive or medium-speed geared systems. In these designs, the gearbox is often included to reduce the speed of the generator. The electric generator with or without a multi-stage gearbox is a critical component of the drive train. The shaft, the main bearings and an electric generator are key elements of the drive train. Early detection of drive train faults is essential in reducing the cost of turbine O&M.
Fig. 11 Variable speed turbine components reliability [56]
Prior Art

Research

The challenge in effective drive train CM in electro-mechanical time frames is in ensuring optimal parameters are being monitored with sufficient fidelity, and the expertise exists that allows competent extraction of monitored signal features that constitute reliable diagnostic indicators and can be credibly related to the observed component’s integrity. The dedicated commercial wind turbine CM systems are largely inherited from other rotating machinery industries and are installed as ‘add-ons’ to the standard turbine configuration; these can incur significant cost, however their financial benefit has been indicated to be considerable [59].

Where the drive train is concerned, the current state of the art offshore WT designs favour generator speed reduction and thus may further emphasise these diagnostic challenges. In addition, the existing operating stresses and therefore the operational stress and wear which would provide a wealth of understanding of in-situ sensing, monitoring key degradation parameters in vicinity of known frequent points of failure (e.g. within bearings) can be used to address critical mechanical and electrical failure modes.

In-situ sensing platforms fused with embedded computing facilities that enable the operator to program intelligent diagnostic algorithms such as vibration, acoustic emissions, oil, electric signature and thermal measurement analytics [60]. These sensing platforms enable the monitoring of a variety of key parameters and can continuously utilise monitoring algorithms that enable the operator to program intelligent diagnostic algorithms. These algorithms enable the operator to program intelligent diagnostic algorithms and can continuously utilise monitoring algorithms that enable the operator to program intelligent diagnostic algorithms. These algorithms enable the operator to program intelligent diagnostic algorithms and can continuously utilise monitoring algorithms that enable the operator to program intelligent diagnostic algorithms.
Power Electronics Condition Monitoring

4.6.1 General Background

Condition monitoring of power semiconductor switches has the potential to improve the effectiveness of maintenance trips and prevent unexpected failures. Although not the sole cause of failures, condition monitoring has the potential to improve the failure rate. Condition monitoring involves monitoring the health of the power electronic converter under operation. This includes monitoring the temperature, voltage, and current of the converter. The goal is to detect any anomalies in the converter's operation that could indicate a potential failure.

4.6.2 Prior Art Research

Condition monitoring of power semiconductor switches has attracted attention with the appreciation of the gradual degradation process of the packaging structure. Previous research has primarily focused on wire-bonded power modules. Recent research has also targeted attention with the application of condition monitoring on the gradual aging of the semiconductor switches.

Power semiconductor switches are one of the main causes of failures in power electronic converters. Most power semiconductor switches used for wind turbines are of the wire-bonded packaging structure in which multiple switching chips (silicon dies) are soldered on the DBC (direct bond copper) which provides thermal conductivity and electrical insulation. Bond wires are used to connect the chips to the power module terminals. Fatigue stresses on the material interfaces due to mismatch of the Coefficients of Thermal Expansion (CTEs) which can lead to cracks and eventual module failure due to over temperature.

Examining the service life of power semiconductor switches is essential to understanding aging-to-failure mechanisms. Most power semiconductor switches have a limited service life, and failure can occur after a few years of operation. The aging process is influenced by the operating conditions, such as temperature, voltage, and current. Understanding the aging mechanisms is crucial to managing the OPEX and/or the grid points of view.

Explain the different failure mechanisms and their impact on the service life of power semiconductor switches. This includes temperature-induced failures, overload failures, and electrical overstress failures.

4.6.3 Offshore Wind Turbines

Offshore wind turbines almost invariably involve power electronics in which silicon-based power semiconductor switches are used to handle kV and kA. In addition to the semiconductor switches, a power electronic system typically also includes capacitors and inductors to buffer the switched energy in electric and magnetic forms. A control system, implemented in microelectronics, governs the fast switching process of the packaging structure. Precautionary measures are needed to ensure the safe operation of the offshore wind turbines.
Degradation would increase the power loss and impede heat dissipation. As a result, the internal junction temperature would increase for the same loading condition. However, it has not been possible to directly measure the junction temperature and the temperature rise, if measured, would be masked by the variation of the operating point. The state-of-the-art condition monitoring techniques capture the change of Temperature Sensitive Electrical Parameters (TSEPs) of the device, such as the on-state voltage at a given current [67], the switching transients and power losses which can be estimated from external measurements [68]. This is then analyzed with the internal measurements to model the degradation and predict the remaining lifetime. The change of TSEPs is then related to the change of the internal junction temperature, the change of the operating point, the degradation and the remaining lifetime. In cases with multiple converters and multiple wind turbines, opportunities may exist for developing sensor systems that can monitor the degradation of each device. This would be achieved through historical data and differential measurements. Systems and data processing to improve the signal/noise ratio.

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Table 2: Signals for Degradation Detection

Further to semiconductors, studies have also investigated the failure mechanisms, lifetime characteristics and condition monitoring of capacitors, filters and other components in power electronic systems [70]. Electrolytic capacitors are used in place of metalized polypropylene film (MPPE) capacitors, e.g. in MMC HVDC. Degradation signatures, e.g. variation of operating voltage (V_{MM}, V_{MPP}), (delay of voltage spike), (change of Miller plateau), (change of Kelvin plateaux, V_{KELV}), (change of ESR, ESL) are also being replaced by metalized polypropylene film (MPPE). The traditional objective of condition monitoring is to prevent catastrophic failures. But an optimum maintenance decision also depends on knowing the remaining lifetime. In the wind energy sector, there is no standardization in condition based maintenance yet. As part of the foundation to be established, models for remaining life-time estimation under projected loading profiles are needed. There is evidence that existing models based on accelerated life testing need to be updated to account for the effect of the current condition on future degradation. New models need to be developed that take into account the effect of the current condition on future degradation [69]. In cases with multiple converters and multiple wind turbines, opportunities may exist for developing sensor systems that can monitor the degradation of each device. This would be achieved through historical data and differential measurements. Systems and data processing to improve the signal/noise ratio.
Review of Subsea Cable Assets

4.7.1 General Background

Critical to the integration of offshore energy into the UK energy infrastructure are subsea cables that export the power to shore. Reliability of these cables critically determines the sustainability of power supply, and economic viability of offshore wind farms to interested parties.

Typically, the cost for locating and replacing a section of damaged subsea cable can vary from £0.6 million to £1.2 million for near-shore installations, according to Beale [71]. According to underwriter GCube, offshore insurance claims relating to subsea power cables equated to €60 million in 2015 alone [72].

Maintaining these cables is of critical importance to utilities that face penalties associated with customer minutes lost and revenue generation that cannot be expedited. Failure of cables can lead to overvoltage and overheating, which can cause internal damage to the cable. These tests focus on the electrical and thermal behavior of the cable, and knowledge of the accurate location of the cable, access to cable, and knowledge of the accuracy of the acoustic location of the cable, conducted by divers and video technology require good visibility.

Subsea cables are subject to logistics and accessibility challenges: inspections and repair work are conducted by divers and video technology require good visibility. These tests focus on the electrical and thermal behavior of the cable, as well as mechanical strength during operation [74].

Before supplying to customers, cable companies undertake rigorous tests to ensure cables meet specific pre-sale standards. According to MeyGen [73], current standards in cable stability are relatively broad and non-specific, it is unclear to what standard cables should be built to withstand underwater conditions in high tidal flow conditions. Moreover, there are no modelling or testing methodologies that deal with cable stability under different wave conditions. The prevailing environmental conditions are due to wear-out mechanisms failure of armour and sheath, and third party damage (27%) (48% environmental conditions)

To date, published reliability data on subsea cables is relatively sparse and case-specific. According to a report by the utility company Scottish and Southern Energy (SSE), the predominant failure modes for subsea cables are related to environmental conditions (48%) and third party damage (27%). The failure modes for offshore cables are related to environmental conditions, such as corrosion and abrasion. Third party inflicted failures are due to wear-out mechanisms and failure of armour and sheath. Inspections and repair work are conducted by divers and video technology require good visibility. Subsea cables are subject to logistics and accessibility challenges: inspections and repair work are conducted by divers and video technology require good visibility.

Overvoltage and overheating can cause internal damage to the cable. These tests focus on the electrical and thermal behavior of the cable as well as mechanical strength during operation [74].
Table 3 Subsea cable faults over a 15 year period

Source: Scottish and Southern Energy (SSE)
Prior Art Research

Cable abrasion and corrosion rate measurements are detailed in an IEC standard [75]. In the abrasion test, a cable is subjected to a mechanical test in which a steel angle is dragged horizontally along the cable. The test is conducted to verify the robustness of cables to potential damage caused by the installation process, therefore test results are not applicable to actual abrasion behaviour during cable operation.

However, once cables are in operation, they become more difficult to monitor due to the long distance between onshore substations and offshore windfarms. Commercial state-of-the-art monitoring systems focus on internal failure modes, including Partial Discharge monitoring and Distributed Strain and Temperature Measurement System (DST). However, given the restrictions in data availability and the economic value of cable assets, monitoring and predicting the condition of cables is crucial to utility companies.

HOME Offshore project proposes a fusion prognostic approach to predict the RUL of submarine cables. This model will include environmental factors such as changing water temperature and third party activities. The challenge is to monitor the thermal condition of submarine cables, which is complex and requires advanced technologies.

The HOME Offshore project proposes a fusion prognostic approach, identifying that 70% of cable failures are associated with external damage. Therefore, offshore assets must be monitored to detect and localize any external fiber damage on the cables. Operators can detect and localize any internal fiber damage on the cables by analyzing outputs from the DST's printouts at onshore substations. Operators then conduct regular inspections by divers or ROVs to confirm cable status and surrounding environments.

Regarding cable failure predictions, very little has been reported on cable wear out mechanisms due to corrosion and abrasion. Larsen-Basse et al [76] developed a localised abrasion wear model but only for a section of the entire cable route, and did not include corrosion and scouring. Wu [77] developed a model of abrasion and corrosion but this requires cable movement to be available as input into the model. Both approaches are limited and come from a very limited number of specific cases. In contrast, the HOME Offshore project proposes a fusion prognostic approach to predict the RUL of submarine cables, which is complex and requires advanced technologies.

Heriot-Watt University used a 15-year historical dataset and developed methods to estimate the remaining useful life (RUL) of cables. However, the dataset only includes data from a very limited number of specific cases. In contrast, the HOME Offshore project proposes a fusion prognostic approach to predict the RUL of submarine cables, which is complex and requires advanced technologies.

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4.8.1 General Background

Integrated data-driven condition monitoring - large-scale data analytics

4.8 Large-scale data analytics

on demand for missing values).
Prior Art Research

The state-of-the-art in condition monitoring for wind farms focuses on online and continuous analyses \cite{82,86} of various component states. Emerging trends include smart monitoring with built-in auto-diagnostics, and automated classification and prediction functions, which rely on data-intensive methods, such as neural networks \cite{87}. The process typically involves real-time signal processing and feature extraction to detect developing failures. Key signals and the condition monitoring algorithms are trained by various component models and subcomponents. The process will integrate actionable patterns across the home offshore project to identify key signals and the condition monitoring algorithms to detect developing failures. We will combine these models with domain knowledge-driven models to develop an intelligent decision support process, where experts will co-operate with condition monitoring algorithms to identify key signals and actionable patterns across the home offshore project.
signal component/turbine granular approaches) to identify actionable decisions.

### 4.9. Telecommunication Technologies

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<th>Jitter</th>
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Table 4: Basic comparison of telecommunication technologies.

The problem here is far more complex and requires even more operation of robust and semi-autonomous systems. They may require more advanced condition monitoring and they may require multi-terminal high-voltage DC (MT HVDC) [93].

In future wind farms will be larger, more complex and further from shore. They may be part of a network of windfarms from shore. They may be part of a network of windfarms from shore. They may be part of a network of windfarms from shore. They may be part of a network of windfarms from shore.

Research into telecommunications does not form a direct part of the HOME offshore research project. It informs many of the other themes, and is thus included as a general background section in this position paper.

### Table 4: Basic comparison of telecommunication technologies

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Table 4: Basic comparison of telecommunication technologies.
In the context of telecommunication networks, latency is the delay between the sending of data from one terminal to its receipt at another terminal. There are a number of sources of latency in a telecommunication network, but given the geographic distances involved in a typical MTDC system the dominant factor will be the delay associated with the propagation of the signal through the communication medium (optical fibre, copper or free space in the case of wireless communication).

Latency is a critical metric where the telecommunication link is carrying information to be used in real-time control, and knowledge of the maximum latency that can occur is essential to the control system design. Where the telecommunication link is delivering enhanced system performance, but is not critical for control, knowledge of the variability of the latency is of interest. This variability is termed jitter, and this metric can be expressed using a variety of standard statistical measures for time-varying signals.

Table 3 provides a basic comparison of the key features of a selection of the most common telecommunication network technologies. This table shows that the dedicated microwave technologies offer the best performance in terms of latency, jitter and security, but that they are also the most expensive to implement. Dedicated fibre optic links are most expensive to implement, but they are also the most reliable and secure, and these are also the dominant factor in terms of latency for MTDC systems. Dedicated microwave technologies offer the best performance after the dedicated fibre optic technology, and these are also the most expensive to implement. Dedicated fibre optic links are most expensive to implement, but they are also the most reliable and secure, and these are also the dominant factor in terms of latency for MTDC systems.

The selection of network protocols is a key factor in determining the overall delay in sending information across a telecommunication network. Protocols that involve a sequence of data exchanges between the two network terminals for control, knowledge of the variability of the latency is of interest. This variability is termed jitter, and this metric can be expressed using a variety of standard statistical measures for time-varying signals.

Simulating power systems utilising telecommunication networks is not straightforward and typically involves using two separate dedicated simulators: a time-stepped analogue simulator for the power system component and an event-based digital simulator for the telecommunication network component. A time-stepped analogue simulator is not straightforward and typically involves using two separate dedicated simulators: a time-stepped analogue simulator for the telecommunication network component and an event-based digital simulator for the power system component. Simulating the two separate dedicated simulators will incur multiple latency delays. For MTDC systems it is necessary to establish the connection across a geographical distance involved in a typical MTDC system. The selection of network protocols is a key factor in determining the overall delay in sending information across a telecommunication network. The selection of network protocols is a key factor in determining the overall delay in sending information across a telecommunication network. The selection of network protocols is a key factor in determining the overall delay in sending information across a telecommunication network. The selection of network protocols is a key factor in determining the overall delay in sending information across a telecommunication network.
where information packets may arrive out of order. The model is also capable of simulating switched packet networks, the playback of actual captured network performance. The jitter may be created from parameterised statistical profiles or accurately simulating constant and variable network latency. 

The PSCAD Telecommunication network model is capable of accurately simulating constant and variable network latency.

**Fig. 13** PSCAD Telecommunication model block diagram
Research into offshore wind-farm condition monitoring and O&M is ongoing and the HOME Offshore project strongly complements a number of national and international initiatives in allied areas. The generation of real-world, or high fidelity, synthetic signals. The need for research to inform policy and legislation to assess both autonomous systems (e.g., drones) beyond line of sight.

Examples include:

- The opportunity to use CM sensors to identify incipient failure during the initial life of the offshore assets. This is a period where cost to the OEM is largest due to the warranty contract. This offers maximum incentive to the OEM to embed new techniques. While the types of early-life failures are different to normal wear-out, potential exists to use these new advanced sensors to assess both.
- The need to design ICT to manage data flows that may be required during the initial life of asset (e.g., CM of farm in 20 years).
- The need to design ICT to manage data flows that may not be the organisation which would need to use it. The HOME Offshore project will take a multi-disciplinary approach to tackle these and other problems. More information is available on the project website www.homeoffshore.org.

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Fig. 13 A Mohamed, University of Manchester, 2018 from [56]

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Fig. 16 M Barnes, University of Manchester, 2018

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Fig. 36 A Mohammed, University of Manchester, 2018 from [56]
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