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Decarbonising Maintenance Operations in Offshore Wind: An Assessment Model for Vessel Usage, Fuel Demands, and the use of Hydrogen as an Alternative Fuel

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Abstract

Offshore wind Operations and Maintenance (O&M) has been identified as a focal point for vessel decarbonisation. However, little research has been conducted into the current levels of fuel demand and associated emissions from these vessels. A detailed understanding of current fuel demands is a vital component in assessing the feasibility of utilising alternative fuels to power these operations. Prior research in wind farm life cycle assessment has shown that modelling of O&M activities, accounting for failure rates, is fundamental for accurate prediction of fuel consumption. However most current O&M models are designed to evaluate cost balance and wind farm site availability, rather than vessel usage. This study presents a new methodology and novel tool, which simulates vessel movement around a wind farm array, allowing detailed assessment of vessel usage, fuel consumption and emissions during O&M activities. This has been coupled with a wind to hydrogen production model in order to evaluate the feasibility of decarbonising these vessels with hydrogen produced by wind powered electrolysis. Initial results for a reference case study showed 16-18% of the annual production of the wind farm would need to be diverted to hydrogen production to meet the O&M vessel fuelling demands. The value sits within the range of average current curtailment levels for UK wind farms, illustrating the potential to alleviate these issues by instead diverting to hydrogen production to fuel service vessels. The analysis also revealed a significant proportion (73%) of fuel consumption is attributed to in field loitering. As such, it is recommended that technology used to maintain vessel position when idle in field should be a focus of efficiency improvements. The emissions contribution from O&M vessels were calculated to be 0.002 ktCO2e per GWh, consistent with that reported by the industry. Therefore, the author concludes the tool presented in this study is applicable to LCA analysis as well as research into alternative fuels for offshore O&M vessels.

Keywords: Offshore Wind Energy, O&M, Hydrogen Production, Vessel Decarbonisation

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Abbreviations

CO2e	Carbon Dioxide Equivalent
CTV	Crew Transfer Vessel
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
LCA	Life Cycle Assessment
O&M	Operations and Maintenance
SOV	Service Operations Vessel

1.0 Introduction

The renewable energy industry has seen substantial growth over recent years. This has been driven, by the increasing need to transition away from a fossil fuel-based energy system and the impacts it is having on the climate. With the widespread application of technology such as wind and solar energy generation, the UK's electricity network now has almost half of its production coming from renewable sources (Figure 1) [1]. However, to meet the Paris agreement net zero energy goals by 2050, it is not only the electricity system that needs to be decarbonised. There is still a long way to go to utilising renewable energy sources in sectors such as heating and transport.

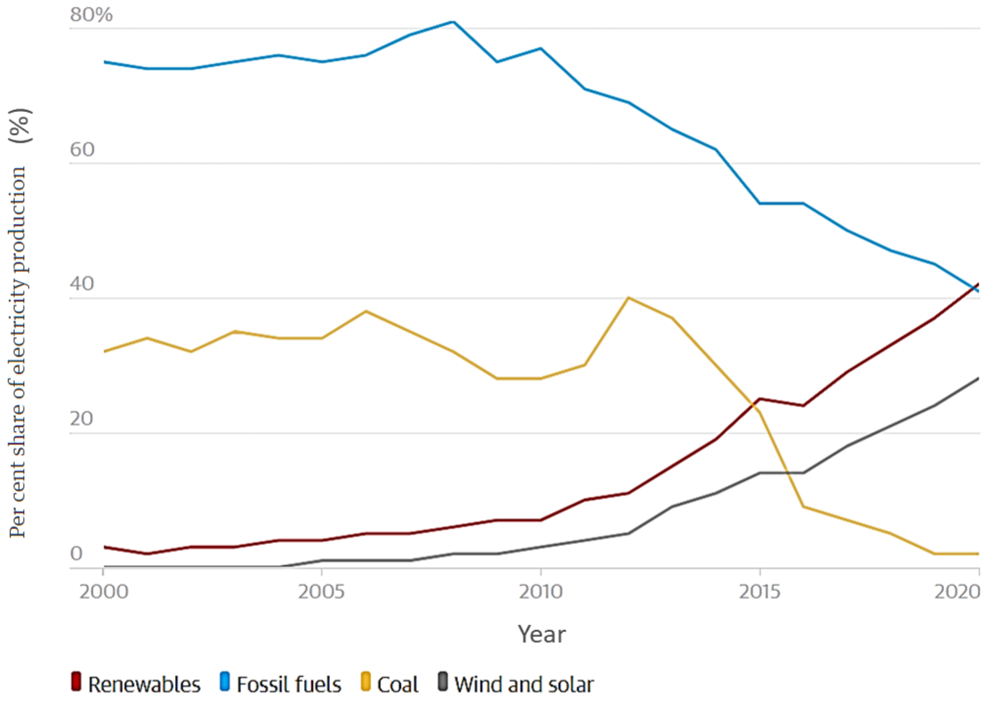


Figure 1: UK Electricity Production Trends by Energy Source (Source: Guardian UK [2])

This project aims to investigate the emissions associated with the use of vessels in the offshore wind industry. Section 1.1 introduces the maritime sector as a whole, providing a background on the current emissions and highlighting opportunities for emissions reduction. In section 1.2 the selection of offshore wind as the focus of the study is explained, followed by a detailed literature review of the current research in this area. Specific aims, methodology and analysis undertaken for the study are presented in the final half of this report (Sections 3 - 7).

1.1 Energy and Emissions in the Maritime Sector

The maritime sector is vital to the global economy with 80-90% of all trade in goods transported by sea[3]. Despite sea transport being considered most efficient in terms of CO_2 per tonne-km, the scale of use means it is a significant contributor to global emissions. The International Maritime Organisation (IMO) estimates maritime freight to account for 3% of Global CO_2 emissions[4]. This figure is expected to grow as other sectors rapidly decarbonise and with the projected increase in demand on sea trade (Figure 2 and Figure 3)[5].

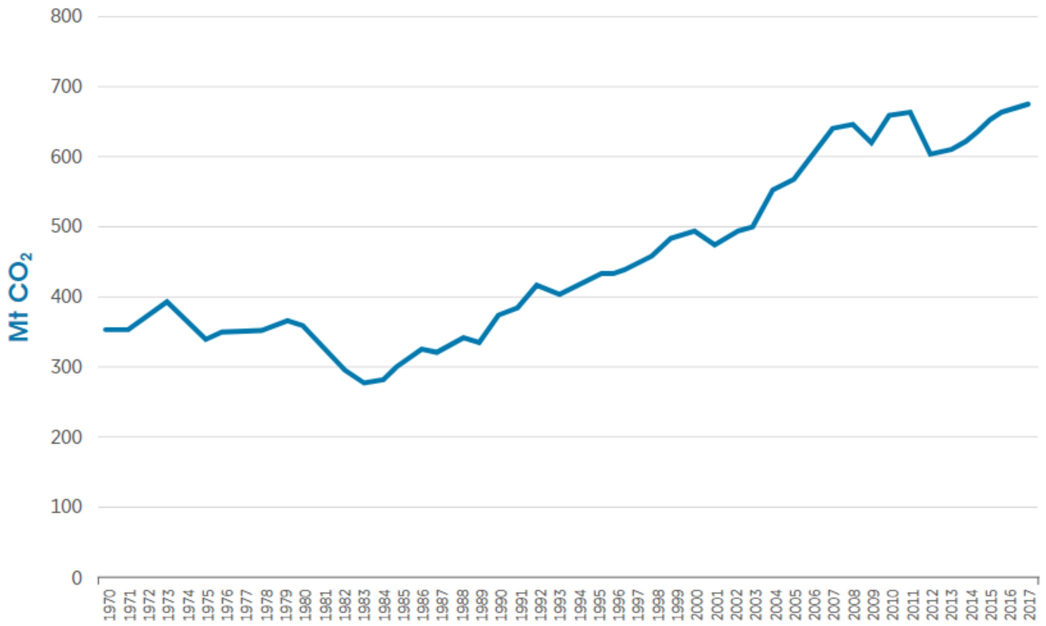


Figure 2:Historical trend in Carbon dioxide Emissions associated with International Shipping (Source IRENA 2019)

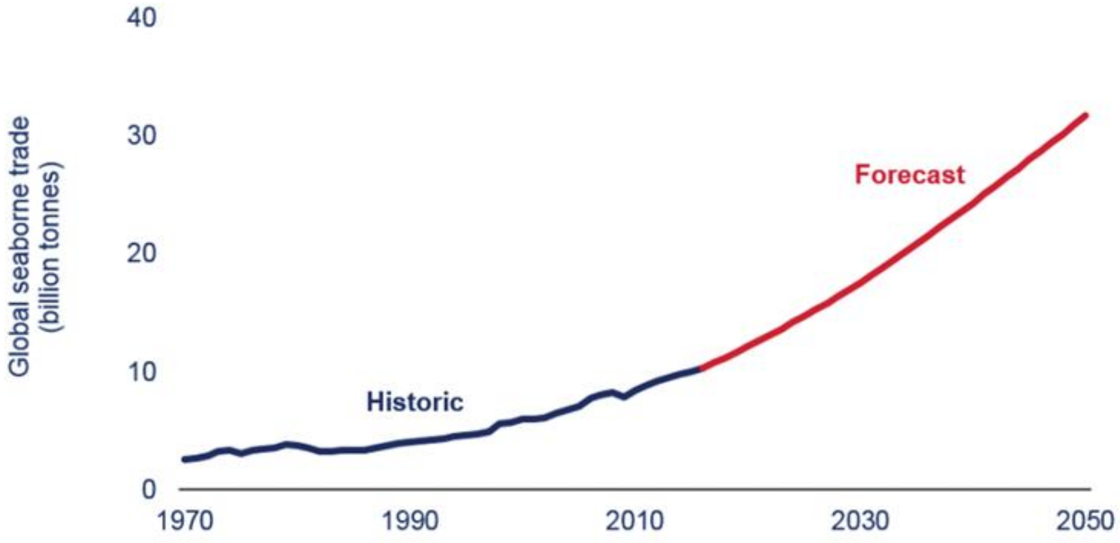


Figure 3: UK Department for Transport Projections of Global Seaborne Trade (Source DfT 2019)

Currently the main energy source for ship propulsion is marine gas oil (MGO), marine diesel oil (MDO) and heavy fuel oil (HFO), all of which are fossil fuels derived from petroleum (Figure 4). Burning these fuels releases significant amount of CO_2 as well as other greenhouse gases such as sulphur oxides (SOx) and nitrogen oxides (NOx). The shipping industry is considered one of the hard to decarbonise sectors as large amounts of fuel is required between ports, due to the weight and range of vessels. As such, shipping is particularly reliant on high energy density fuels, and decarbonisation options such as electrification are more difficult[6]. An EIA report showed in 2019 fossil fuel consumption in international shipping equated to 2389 TWh[6].

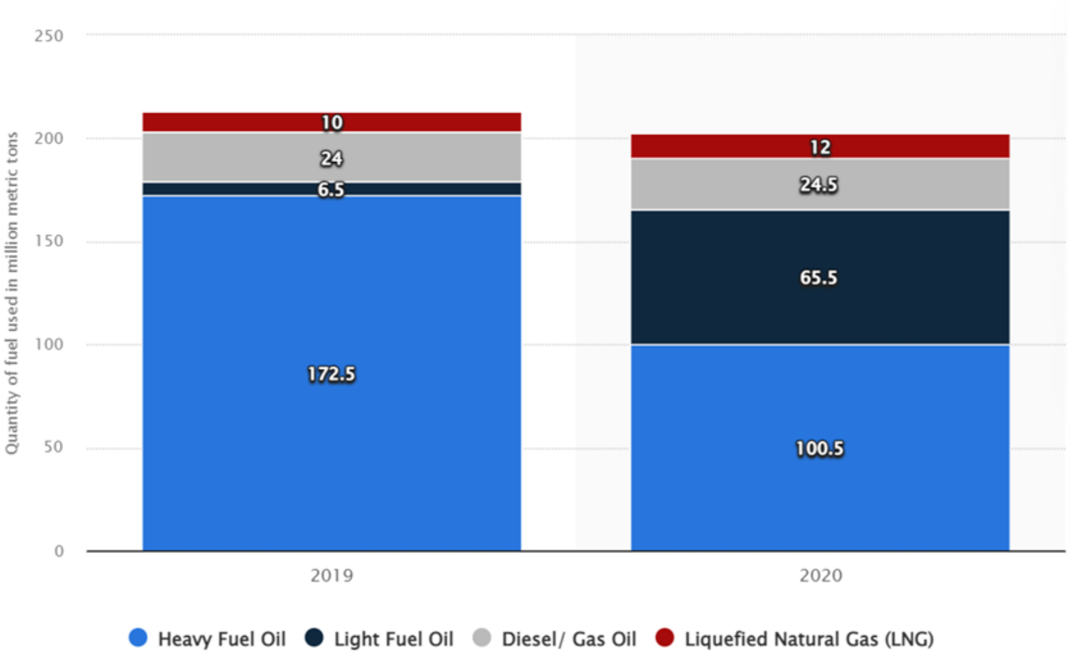


Figure 4: Global fuel consumption for shipping, by fuel type (source Statista 2022)[7]

A European Parliament report indicates that, without intervention, international shipping may account for 17% of Global CO_2 emissions by 2050 [8]. As such the IMO has set out policy for the sector to reduce its greenhouse gas emissions by 50%, from a 2008 baseline, by 2050 [9]. Currently, the IMO Greenhouse Gas study predicts a business-as-usual path would lead to emissions representing 90-130% of the 2008 baseline by 2050 [4]. This has prompted governments and industries across the globe to set out plans to achieve zero-emission vessels, as summarised in Table 1.

Table 1: Key industry and government agreements towards zero emissions vessels.

	Mission Statement	**Signatories**
Getting to Zero Coalition[10]	Commercially Viable Zero-Emission Vessel for deep-sea trade routes by 2030. Including supporting infrastructure (fuel production, distribution, and storage)	150 companies within the maritime, energy, infrastructure, and finance sectors, supported by governments.
Operation Zero [11]	Zero-Emission Vessels for the North Sea Offshore Wind Farms by 2025	Aberdeen Harbour, Associated British Ports, Aluminium Marine Consultants, Artemis Technologies, BAR Technologies, Bibby Marine Services, Cedar Marine, Chartwell Marine, Esvagt, GE Power Conversion, Global Marine Group, Lloyd's Register, Maritime Skills Alliance, MJR Power and Automation, North Star Renewables, Offshore Renewable Energy Catapult, Orsted, Parkwind, Port of Cromarty Firth, Port of Esbjerg, RWE, Seacat Services, Siemens Gamesa, Strategic

		Marine, The Workboat Association, Tidal Transit, Vattenfall, Windcat Workboats, ScottishPower Renewables
Clydebank Declaration [12]	Green Shipping Corridors (zero-emission maritime routes between ports)	Australia, Belgium, Canada, Chile, Costa Rica, Denmark, Fiji, Finland, France, Germany, Ireland, Italy, Japan, Republic of the Marshall Islands, Morocco, Netherlands, New Zealand, Norway, Palau, Singapore, Spain, Sweden, GB&NI, USA

1.1.1 Routes to Decarbonising Vessels

The main areas being explored to reduced emissions in the maritime sector can be categorised into, efficiency improvements, technologies to treat exhaust emissions, and alternative propulsion technology, as described in the following sections [5], [13]. Although much of the industry focus is currently on alternative propulsion technologies that make use of renewable energy sources, a report commissioned by the international chamber of shipping (ICS) suggests that it would take the entire current global renewables production to meet the predicted demand in the sector[14]. As such, it is likely the most feasible approach will have to involve a combination of developments in all three categories.

1.1.1.1 Exhaust Treating

The exhaust treating options focuses on reducing emissions associated with current fuels usage via implementing technologies such as SOx scrubbers, catalytic reduction and exhaust gas recirculation [15]. However, this technology only represents minimal reductions and does not tackle the root cause of emissions being the fossil fuel usage. As global demand for shipping increases, these technologies will fall short on achieving the emissions reduction required. It is concluded that exhaust treating is only viable as a short-term mitigation strategy that can be implemented to bridge the gap during the transition to alternative fuel and zero-emission technologies.

1.1.1.2 Efficiency Improvements

Improvements in efficiency appear to be a key aspect of the IMO strategy. The IMO has set out regulations on energy efficiency in ships through the Energy Efficiency Design Index (EEDI) in 2011, and a new Energy Efficiency Existing Ship Index starting in 2023 [9], [16]. Efficiency improvements are being made via improved ship designs, such as new paints and hull coatings to reduce fouling, and air lubricants to reduce hull drag [15], [17]. Another leverage point that has been identified for efficiency improvements is operational behaviour. Balcombe *et al* reports reducing vessel transit speed, known as slow steaming, can reduce overall emissions despite increased operational time, with estimates of 11% reduction from container ship emissions[17]. Other novel developments such as assistive wind propulsion are being explored to improve fuel efficiency by reducing load on engines[15]. Efficiency improvements are likely to be an enabling factor to the implementation of alternative propulsion technologies by reducing the overall energy demands.

1.1.1.3 *Alternative Propulsion*

There is agreement across all literature that alternative fuels will be needed to achieve the IMO target of 50% reduction in vessel CO_2 emissions. As can be seen from the latest Getting to Zero Coalition report, 7 key alternative propulsion technologies/fuels have been identified, with hydrogen gaining the most interest (Figure 5) [18]. Few alternative fuels can match the volumetric energy density found in fossil fuels (Figure 6). As such a key challenge of implementing alternative fuels in the maritime sector arises from the volume of fuel that needs to be carried to provide sufficient energy to meet the demands of a voyage. Although electric battery propulsion has found some application for shorter journey vessels such as inter island ferries, there are concerns over their use [5]. Specifically due to the weight and limited range of current battery technology [15]. For the maritime sector fuel-based energy carriers are preferred.

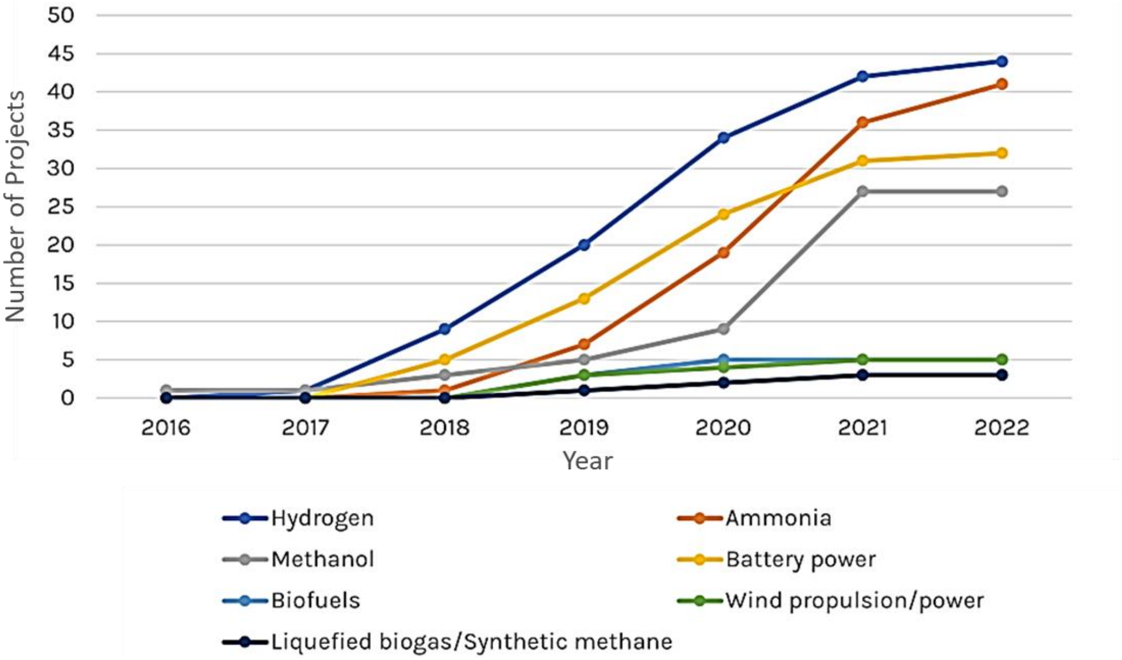


Figure 5: Number of global ship technology projects by fuel focus (Source GettingToZero 2022)

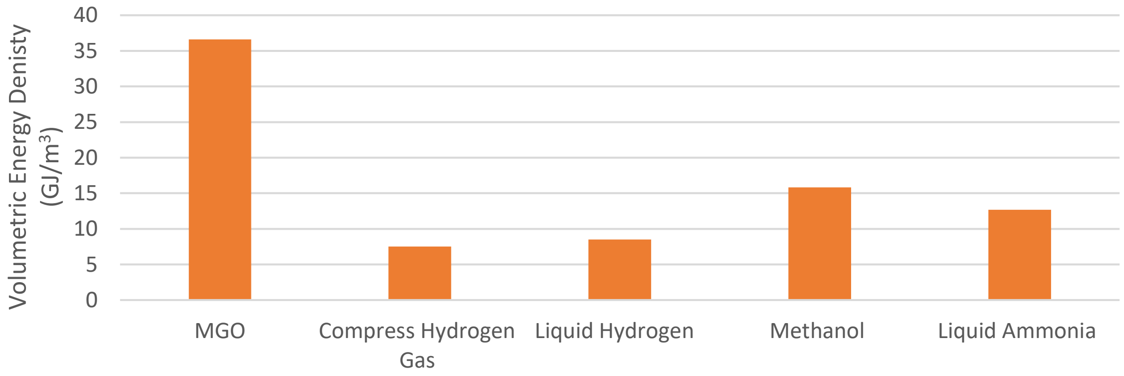


Figure 6: Comparison of the volumetric energy density of proposed marine fuels

1.1.1.3.1 Hydrogen

Hydrogen can be produced from the electrolysis of water making use of renewable electricity (Figure 7). This is known as green hydrogen and is considered a clean fuel, as opposed to Grey or Blue Hydrogen which are derived from fossil fuels. The advantage of hydrogen is its relatively high production efficiency. Hydrogen is drawing interest as a marine fuel as it has higher energy density than battery technologies, and due to the compatibility with current combustion engines. However, the relatively low volumetric energy density of hydrogen in a gaseous form means it must either be compressed to high pressure or liquified at cryogenic temperatures[5]. This means significant changes to storage and refuelling infrastructure would be needed, bringing associated technical and safety challenges [19]. Due to the scale and expected cost of the infrastructure changes, hydrogen derivatives with more favourable properties, are also being considered (Figure 7). The key properties of these fuels are summarised in Table 2.

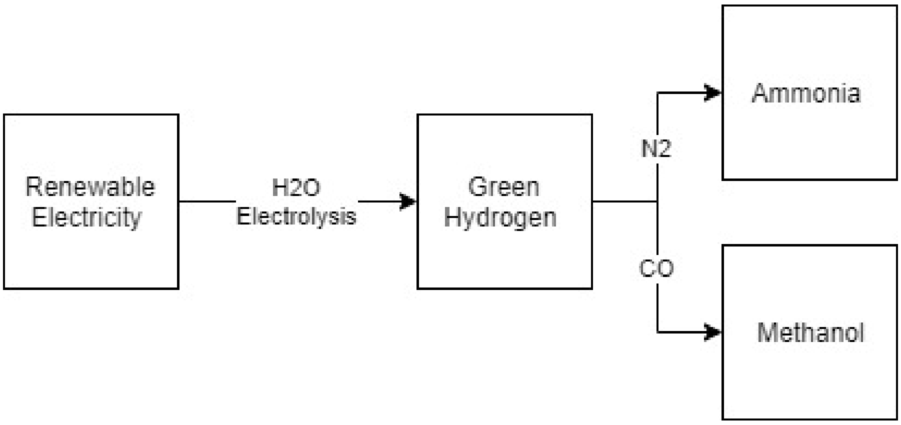


Figure 7: Schematic of Power to Liquid Fuel Operations (Adapted from IRENA 2019)

1.1.1.3.2 Ammonia

Ammonia liquifies at -33 C at atmospheric pressure, and therefore does not require high-pressure infrastructure to be implemented on vessels. For this reason, and because it has a higher volumetric energy density than hydrogen, it is being considered as a marine fuel [3], [5]. However, there are challenges related to its toxicity and low efficiency of production (~50%)[5]. Ammonia can be used in a fuel cell propulsion system or burned in traditional combustion engines.

1.1.1.3.3 Methanol

Methanol has the highest energy density of the alternative fuels (Figure 6) as well as closer characters to current fossil fuels (Table 2) [3], [5]. This mean methanol can easily be implemented without significant changes to storage and refuelling infrastructure. As such methanol fuelled cargo ships have already been demonstrated. However, high production costs are seen as a barrier to the implementation of menthol at a large scale [3], [5].

Table 2: Comparison of key properties of alternative fuels [3], [5]

Fuel Type	Volumetric Energy Density (GJ/m^3)	Storage Pressure (Bar)	Storage Temperature (°C)
MGO	36.6	1	20
Methanol	15.8	1	20
Liquid Ammonia	12.7	1 10	-33 20
Liquid Hydrogen	8.5	1	-254
Compressed Hydrogen	7.5	700	20

1.1.2 Policy and Regulation Challenges

Decarbonising the maritime sector comes with many unique challenges. One significant issue is the requirement for international coordination and agreement on the route to transition in order for vessels and port infrastructure to be compatible across the global network[13]. Currently it is unclear which alternative fuel is most suitable. Therefore, there will need to be multi-stakeholder alignment for decisions making on which alternative fuel pathway to follow. Additionally, maritime bodies cannot pass new regulatory frameworks for the use of these alternative fuels until all safety risks are understood. This may present a barrier to innovation and new technology implementation [13].

1.1.3 An Opportunity and Leverage Point

It has been recognised that the energy generated by offshore wind farms is likely to play an important role in the production of future maritime fuels, as described by Figure 7. The offshore wind sector also relies heavily on vessels and therefore provides an opportunity to act as a base for demonstration of both production and consumption of new fuels. This has been identified as a leverage point to maritime decarbonisation, leading to the Operation Zero agreement (Table 1).

1.2 Scope of Project

The present study addresses the application of hydrogen as an alternative fuel for offshore wind vessels. The boundaries of research are confined specifically to the energy demands, and emissions associated with vessel usage in offshore wind, and the feasibility of meeting these energy demands with hydrogen. The energy required for the production of hydrogen is also investigated. Consideration to technical infrastructure and safety challenges were placed out of scope for this study.

Hydrogen was chosen as the fuel of interest for this study due to the possibility of directly producing and utilising wind energy and sea water, as opposed to ammonia and methanol which require additional reagents. Additionally, the GettingToZero report shows hydrogen as gaining the highest current interest of the three alternative fuels [18]. With the present interest in leveraging offshore wind as a springboard to decarbonise maritime industry, it is understood to be a highly relevant area that requires present research input. This project hopes to identify knowledge gaps and provide useful contribution to current research in the area.

2.0 Literature Review

In this section published literature is reviewed to illustrate the current understanding of maritime operations in offshore wind. Section 2.1 explores the methods presented in the literature for assessing vessel emissions. Section 2.2 delves deeper into modelling and simulation techniques of offshore wind operations. Following this a scoping review of hydrogen as a fuel and more specifically current trends in wind powered hydrogen research is explored. Findings from the literature review are summarised and the key research gaps highlighted in section 2.4, which are used to define the project aims and objectives (Section 4).

2.1 Maritime Operations in Offshore Wind

The offshore wind sector is heavily reliant on marine logistics, across all stages of the life cycle, for the transportation and accommodation of workers, movement and storage of parts and installation and access to turbines. The common types of vessels deployed are listed in Figure 8. It is estimated that the cost of vessel charter accounts for 50% of the total wind farm costs over its lifetime [20]. The majority of this comes from the operations and maintenance (O&M) stage which lasts 25-30 years and primarily makes use of Crew transfer vessels (CTVs) and Service Operation Vessels (SOVs) [21].

Figure 8: Common Vessel Types used at each stage of a wind farms life cycle

Driven by the need to tackle the climate crisis and meet net-zero goals, there have been large injections of funding and increasing development of offshore wind energy. Consequently, an increased demand is expected for offshore wind service vessels. Offshore Wind vessel growth scenarios, published by ORE Catapult, estimate 1,400 new vessels will be built between now and 2050 [15]. Additionally, the report shows that there is an expected transition from CTVs towards more SOV usage as wind farm sites move further offshore [15].

With the fundamental role vessels play in the economics and operations of wind farms significant research has gone into modelling and optimizing their use, predominantly focused on improving profits (Section 2.2.1). Now these vessels have been identified as a key target for reducing emissions in the industry. Offshore wind was born out of the need to produce clean energy. It is recognised as a significant and necessary step for the industry itself to make use of this energy to fully run operations with clean fuels. The vision of the sector is to demonstrate a 100% clean industry and be a launch-pad for broader maritime decarbonisation [11], [15].

2.1.1 Vessel Emissions in Offshore Wind

2.1.1.1 Emissions Predictions from Life Cycle Assessments

Environmental impact and emissions associated with offshore wind has been a point of research throughout the development of the sector. This is commonly achieved through life cycle assessments (LCA). LCA is an analysis technique employed by the International Organization for Standardization (ISO), for assessing the environmental impacts associated with all stages of a products life [22]. The analysis considers raw materials extraction, processing, product manufacturing, distribution, use and end of life. Despite this, of the literature available on LCA of wind farms, very little detail is reported on the impacts associated with vessel usage. It is possible that this is due to the nature of LCA's focussing on embodied carbon of materials and equipment. For example, a review paper on wind farm LCAs makes no reference to vessel usage but details materials, thus the authors conclude more efficient equipment production and new materials would have the most impact of CO2e emissions[23]. The review paper places emissions associated with the operational phase in the context of fossil fuel-based energy production systems and consequently interprets wind farm operations to be of minimal impact in comparison. This is just one example of the operational phase falling out of scope of focus for LCAs resulting in a lack of detailed analysis of fuel usage by vessels during operations.

Focusing on whole system and embodied carbon emissions during LCAs means that high-level assumptions are applied to vessel utilization and fuel usage. Garcia-Teruel *et al* identified that many studies apply the same assumptions for offshore operations as for onshore, such as fuel consumption based on road transport [24]. The authors link this to underestimation of the contribution of emissions from fossil fuel consumption of vessels during the O&M stage [24]. For example, Huang *el al* applied high-level assumptions on vessel fuel consumption. The results from their study showed fossil fuel usage to have the highest contribution to environmental impact across all stages of a wind farm's life cycle but calculated the largest proportion to be from the installation stage [25]. In contrast Arvesen *et al* applied assumptions on vessel utilisation based on an operational technical report of an active wind farm and found 48% of the life cycle vessel emissions to come from the O&M stage.[26].

The combination of comparing the relative impacts during operations with the oil and gas industry, and high-level assumptions leading to underestimation of vessel utilization means fuel consumption by vessels had not been identified as a focus point for deeper research. The academic community has extensively explored material design in LCAs, such as the study by Raadal eta [27] which focuses on different foundation designs. Prior LCA studies have failed to evaluate impacts from vessels and limited detailed modelling of vessel emissions is presented.

While one explanation for limiting assumptions is due to the nature of LCAs focusing on a high-level whole system view. Garcia-Teruel *et al* also suggests the lack of modelling of emission from vessel utilization could be a result of limited data and operational experience for the wind sector, referring to limited information in the Ecoinvent database used for LCA assessment [24]. However, with the industry becoming more mature there is now more publicly available data on component reliability and vessel usage. A System Performance, Availability and Reliability Trend Analysis (SPARTA) report is published annually offering key data gathered from over 60% of UK based offshore wind farms [28]. Information such as this being utilised for more detailed studies of vessel emissions during the O&M phase [15]. Such as the emissions benchmarking study conducted by ORE Catapult that reports CTV and SOV's are expected to emit 586 and 1042 tonnes of CO2e per vessel per year, respectively.

2.1.1.2 Emissions Predictions from Operations and Maintenance Modelling

Garcia-Teruel *et al* applied detailed modelling of planned O&M maintenance events, based on component failure rates and weather windows, to account for vessel impacts during their LCA of floating offshore wind farms. The authors report that the O&M phase contributed to 41% of the total mean global warming potential, of which 30% was associated with O&M vessels. Additionally, the authors found that across the lifespan of the wind farm, vessel usage contributed the largest proportion of ozone formation, stratospheric ozone depletion and terrestrial acidification impacts. All of which can be attributed to the greenhouse gas emissions from marine fuel combustion. Most significantly, the study demonstrated high sensitivity towards vessel assumptions and highlights the importance of O&M modelling when determining fuel consumption.

The O&M phase of an offshore wind farm life cycle is the longest in duration lasting for 25-30 years [21]. The consistent use of vessels throughout this time means the high contribution to life cycle impacts, found in the studies by Garcia-Teruel *et al* and Arvesen *et at*, is the expected outcome. The analysis of the literature presented here highlights the importance of O&M modelling when evaluating vessel fuel demands. It is expected that this will see increased interest in the research community as the focus shifts towards decarbonising offshore wind operations. Indeed, ORE Catapult predicts carbon footprint will become a key indicator for offshore wind performance as the industry moves away from financial subsidy, and costs scrutiny [15]. As such current approaches to modelling and simulating O&M in offshore wind are reviewed.

2.2 Offshore Wind Operations and Maintenance

The maintenance of offshore wind farms encompasses preventative and corrective intervention strategies in order to maintain high site availability. Where availability is a concept used as a measure of the performance of an asset and is described as the proportion of time that energy production is technically capable [29]. As such O&M strategies effect the overall efficiency and profit margin of a wind farm[20].

One of the major challenges of offshore O&M is that of access, which is limited by weather, sea state and distance from port. Each site will have its own unique mix of these characteristics as well as number, size, and reliability of turbines, all of which influence the O&M strategies employed [20]. At present operators predominantly employ a workboat-based O&M strategy utilising CTVs and SOVs[20]. A brief description of the characteristics of these two vessel types is given below.

Crew Transfer Vessels

- 90% of all O&M vessels deployed for offshore windfarms in the UK .
- Fast and manoeuvrable allowing quick response to failures.
- Developed specifically for access to offshore wind turbines for minor maintenance tasks
- Deployed on a daily bases rather than remaining offshore
- Passengers 12-24, Range 60 NM, Speed 15-30 Knots, Access Limit (Hs) 1.5-2m

Service Operations Vessels

- Adapted from offshore oil and gas industry
- Designed to remian offshore for 2-3 weeks at a time
- Act as a platform for wind farm spoort providing accomodation and equiment storage
- Often instaled with walk-to-work systems to allow technician transfer to turbines
- Often deployed in combination with CTVs emplying mothership consept

2.2.1 O&M Modelling and Simulation

As well as affecting energy production and profit margin, O&M activities are estimated to account for 25-30% of the total lifecycle costs [20], [30]. Therefore O&M modelling has been a high interest area for research. A study by Fox *et al* illustrated that the basis of most O&M modelling research has been on determining the vessel fleets size, mix, and deployment strategy, to obtain an optimised availability-cost balance for the site [31]. This synergy is illustrated by the diagram from A Guide to UK Offshore Wind Operations [29] (Figure 9).

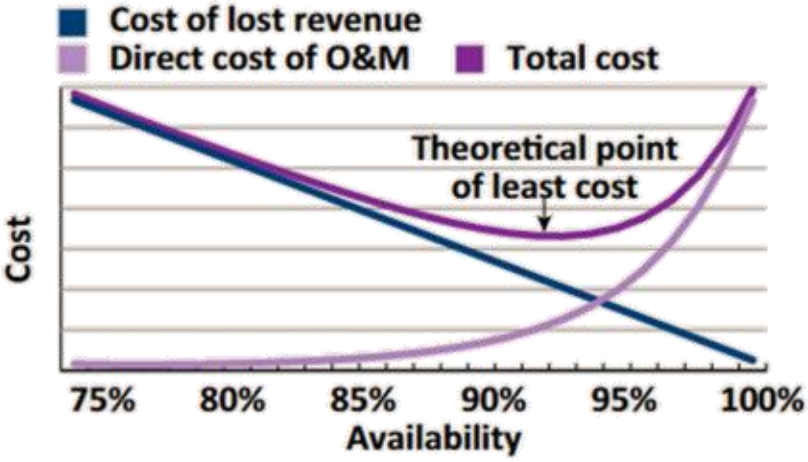


Figure 9: Illustration of Balance Between Cost and Lost Revenue (Source G Hassan 2013 [29] *)*

A review of the literature shows that modelling techniques predominantly consider statistical, or data driven prediction of component failure, alongside practical factors of operations (weather windows) to determine optimal maintenance schedules. Kolios *et el* presented an open access tool, openO&M, which takes failure rates of subsystems, simulated weather conditions and O&M policies in order to determine site availability and power production[30]. The modular nature of the tool is advantageous as it allows the user to focus on the impacts of many aspects of O&M. For example, the authors explore the sensitivity of site availability to vessel mobilisation time [30]. However, the focus of the tools analysis is on how many failures can be fixed and the resultant availability. It is not clear if vessel deployment time is recorded, and there is no consideration to distances travelled. As such it offers limited applicability for determining vessel utilisation, required to estimate fuel consumption for LCA and energy requirements of future alternative fuels.

Similarly, tools such as NOWIcob and Studies by Carroll *et al* apply mathematical failure modelling and evaluate maintenance resources planning in terms of number and type of vessel that should be used[32], [33]. Again, the focus of these studies is on site availability and are designed for strategic planning purposes. Carroll *et al* states vessel travel times are not included. From the literature review it is clear that current modelling of O&M activities is unsurprisingly focused on cost optimization, through vessel deployment strategies. As vessel costs are given by day rates rather than fuel usage, the present models have limited ability to evaluate emissions and fuel demands. To assist research and developments in decarbonising O&M vessels alternative O&M modelling must be developed with a focus on the nature and duration of vessel activities. Nonetheless, a key takeaway from present O&M modelling research is the importance of failure rates, weather windows, parallel maintenance tasks, when developing a model [33].

2.3 Hydrogen as a Fuel

As touched upon in section 1.1.1.3. Hydrogen has been gaining interest as a fuel due to its high energy density and because when burned the only by products are water and oxygen making it one of the cleanest fuels. It is expected to play a critical role in reducing emissions in hard to decarbonise industries such as steel, heating and transportation. Its use as a fuel can be either via traditional combustion engines (Figure 10) or in a fuel cell, in which hydrogen and oxygen are combined producing an electrical output (Figure 11).

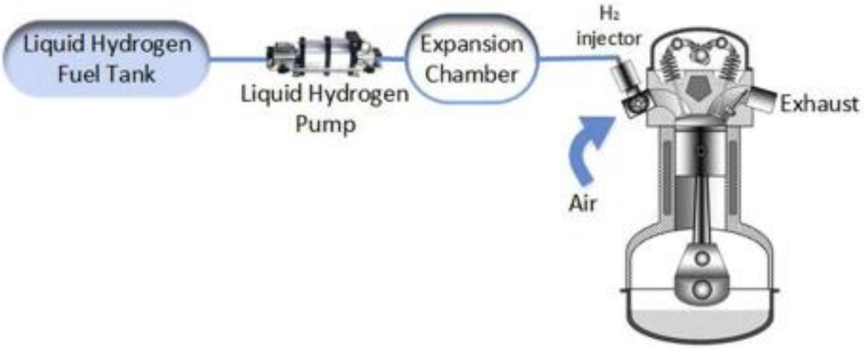


Figure 10: Schematic of a liquid hydrogen internal combustion engine (Source Gurz et al 2017 [34]*)*

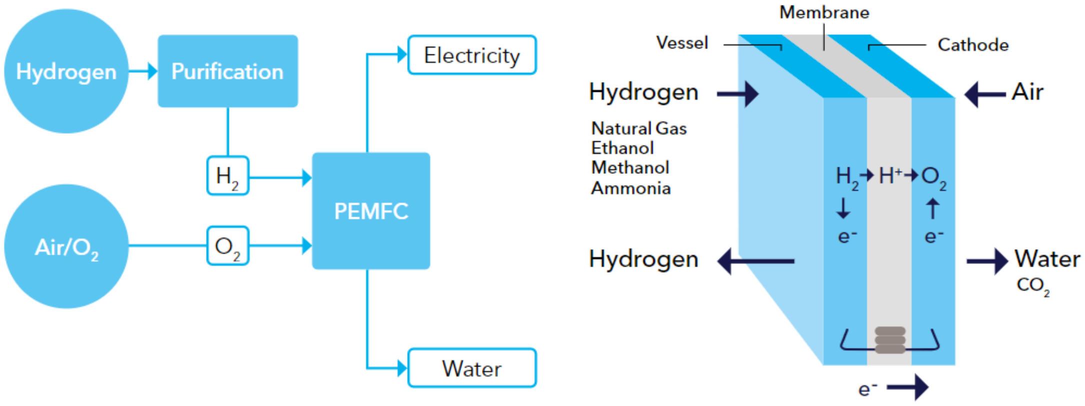


Figure 11: Schematics of a Hydrogen Fuel Cell (Source DNV 2017 [35])

2.3.1 Hydrogen Production Technologies

Hydrogen cannot be considered an energy source itself, rather it is an energy carrier. This means that it must be produced by use of a primary energy source. The majority of the current global hydrogen production is via extraction from fossil fuels and biomass [36] but the area of significant interest is hydrogen produced from water via electrolysis, termed green hydrogen. In this process water is split into hydrogen and oxygen with use of electricity, following the hydrogen fuel cell principle (Figure 11) in reverse. Producing hydrogen in this way means it can act as an energy store for electricity produced from renewables. Three main electrolysis technologies have dominated hydrogen production research in recent years. The key difference being in the type of membrane used in the system (Figure 11). The Advantages, disadvantages, and characteristics of each technology are described in Table 3.

Table 3: Key Electrolysis Technologies for the Production of Hydrogen [37]–[39]

Electrolysis Technology	*Solid Oxide Electrolysis cell (SOEC)*	*Polymer Electrolyte Membrane (PEM)*	*Alkaline (AEL)*
Electrolyte	Ceramic	Polymer	liquid alkaline solution (Lithium or potassium hydroxide)
Operating Temperature (°C)	500-1000	70-90	<100
Feed in Pressure (Bar)	1	30-60	15-30
Efficiency (%)	81-86	67-82	62-82
Advantages	• Availability of materials	• Low minimum load and short start up time therefore suitable for use with varying energy input • High hydrogen purity	• Mature Technology • Low CAPEX

Disadvantages	• Only at research stage • Complex auxiliary equipment requiring more energy (steam generation and high pressure)	• High CAPEX, due to need for rare earth metals	• High minimum operating capacity and slow cold start time 30-60 minutes • Requires constant power feed and continuous operation

2.3.2 Wind to Hydrogen

One of the challenges of wind energy comes from the variable nature of production. Combining offshore wind with hydrogen production provides an energy storage solution for when supply is greater than demand [40]. Additionally, due to capacity limits of electricity grid infrastructure there is an increasing issue of grid congestion[41], [42]. To alleviate this wind farms are paid to shut down, termed curtailment, meaning potential renewable resource goes unutilised[41]. Wind to hydrogen is also being considered as a solution to recover and use the otherwise wasted resource[43]–[45]. As such the academic community has been extensively exploring wind to hydrogen systems.

There is agreement across the literature that the PEM electrolyser technology is most suitable for deployment in a wind to hydrogen system due to its high dynamic response [37], [39]. Meirer *et el* compared the use of PEM and SECO technologies in an offshore wind- sea water electrolysis context[37]. Their study concluded that SOEC had most favourable investment costs and high efficiencies. However, SOEC requires high temperatures, which often takes the form of heat recovery from other processes, this is not available in a wind production context[37]. Additionally, although PEM has lower efficiency the authors calculated the PEM to produce more hydrogen across all scenarios due to the higher capacities feasible with this system[37]. This is particularly pertinent to O&M vessel fuelling context as high demands are expected.

Wind to hydrogen is still in the early stages of development and this is reflected in the literature. The prevailing focus of research is currently on evaluating economic viability by modelling of wind powered hydrogen systems to calculate the levelized cost of hydrogen [40], [43], [45]. The economic landscape is still uncertain. McDonagh *et el* suggests that curtailment mitigation is not enough to secure investment in wind to hydrogen production[45]. However, according to the author's search no study has considered the cost benefits of producing hydrogen to fuel the wind farms service vessels instead of selling to external consumers.

Careri *et al* and Bonacina *et al* do assess hydrogen production for use in transportation and shipping[44], [46]. However, both their studies focus on the hydrogen production and economic feasibility. Careri *et al* suggests that 230,00-606,000 cars could be fuelled by hydrogen from wind curtailment in Germany. Nonetheless, neither study considers the context of expected demands. With the current status of the industry few studies have considered supply and demand analysis.

2.4 Conclusion and Gap Statement

Offshore wind O&M has recently been identified as a leverage point for decarbonising vessels. However, few studies have investigated the expected energy demand, and thus the feasibility of meeting this with alternative fuels. The review of published literature has found that previous work on LCA of wind farms have estimated fuel consumption of O&M vessel to determine emissions impact. However, the high-level assumptions applied in LCA's has resulted in underestimation of the fuel demands of O&M vessels. O&M simulation and modelling has been recognised as vital element for accurate assessment of fuel usage. On review of O&M modelling studies it was found that the prevailing focus of the methodologies is on balancing site availability and O&M costs. A gap in the literature has been found in specific analysis of vessel usage, movements and consequently fuel demands. Further research and developments in this area could advance LCA of wind farms as well as having a significant contribution to the understanding required in decarbonising operations in offshore wind.

While hydrogen is a fuel of interest for vessel decarbonisation, wind to hydrogen production is also a growing research topic. Many studies have investigated the economic viability of addressing current curtailment issues in the wind industry by diverting to hydrogen production. Others have modelled production levels and associated price of hydrogen. While the synergy between wind energy, hydrogen production and vessel fuelling has been recognised. No studies have coupled modelling of wind powered hydrogen production with expected demands from shipping.

3.0 Project Aims and Objectives

This project aims to address the limited research on offshore wind O&M vessel movements and fuel demands, in order to develop understanding of the feasibility of meeting these demands with onsite hydrogen production from wind powered electrolysis. The results of this study aim to add insight towards decarbonising offshore wind O&M with hydrogen as an alternative fuel. It is also hoped that the development of a novel O&M modelling tool that evaluates vessel usage and fuel consumption will add value to future LCA research. To meet these aims, specific objectives for the project were defined as follows:

O1. Construct a novel O&M modelling tool designed to measure vessel movements and utilization to estimate fuel demands.

O2. Develop a hydrogen module that evaluates current fuel demands, converts this to a hydrogen fuel equivalent and calculates the energy required for hydrogen production via wind-powered electrolysis.

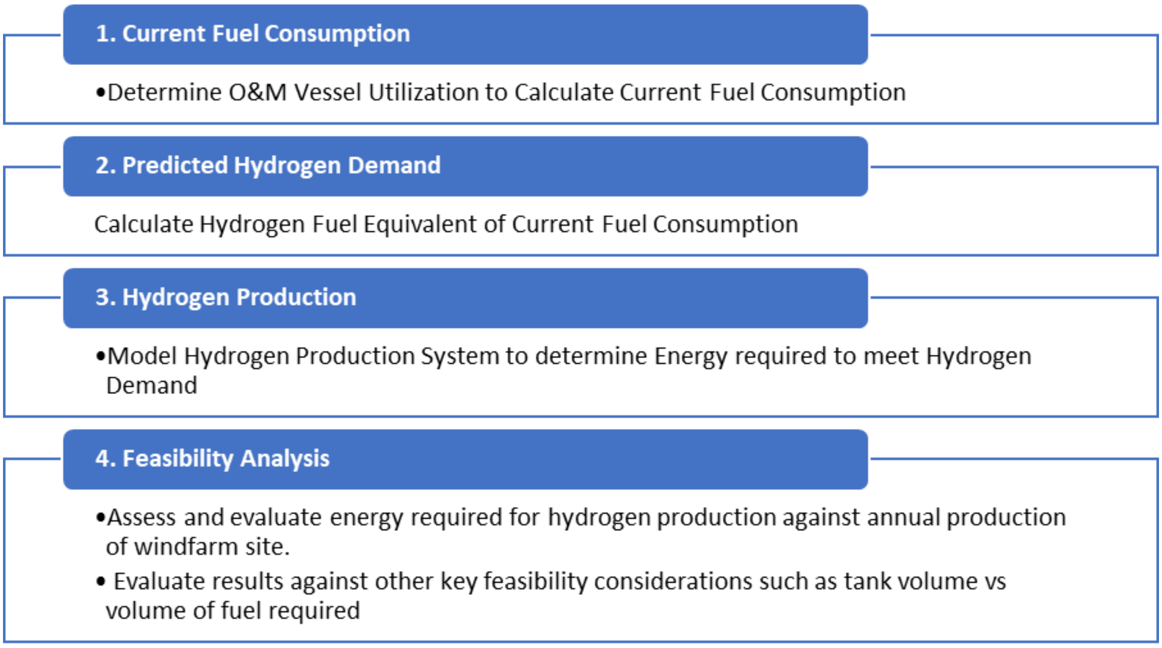
O3. Critically assess and validate the newly proposed modelling tool

O4. Apply the modelling tools to a case study wind farm to explore specific fuel energy demand and emissions.

O5. Explore the expected hydrogen fuels demands of a case study wind farm and compare the Energy required for hydrogen production with the total energy produced by the wind farm to assess the feasibility of supplying O&M vessel with onsite hydrogen production.

4.0 Methodology

This section describes the approach taken, technical analysis and theoretical modelling used to achieve the aims and objectives set out in section 3.0. An overview of the approach taken for this study is described by Figure 12, with a detailed description of the modelling methods provided in following subsections 4.2-4.5.



1. Current Fuel Consumption

- Determine O&M Vessel Utilization to Calculate Current Fuel Consumption

2. Predicted Hydrogen Demand

Calculate Hydrogen Fuel Equivalent of Current Fuel Consumption

3. Hydrogen Production

- Model Hydrogen Production System to determine Energy required to meet Hydrogen Demand

4. Feasibility Analysis

- Assess and evaluate energy required for hydrogen production against annual production of windfarm site.
- Evaluate results against other key feasibility considerations such as tank volume vs volume of fuel required

Figure 12: Overview of Study Approach

4.1 Definition of System and System Boundaries

To study the potential hydrogen demand for fuelling service vessels, and the wind energy production required to produce this hydrogen, a causal loop diagram was created to visualize the many interacting variables within the system (Figure 13).

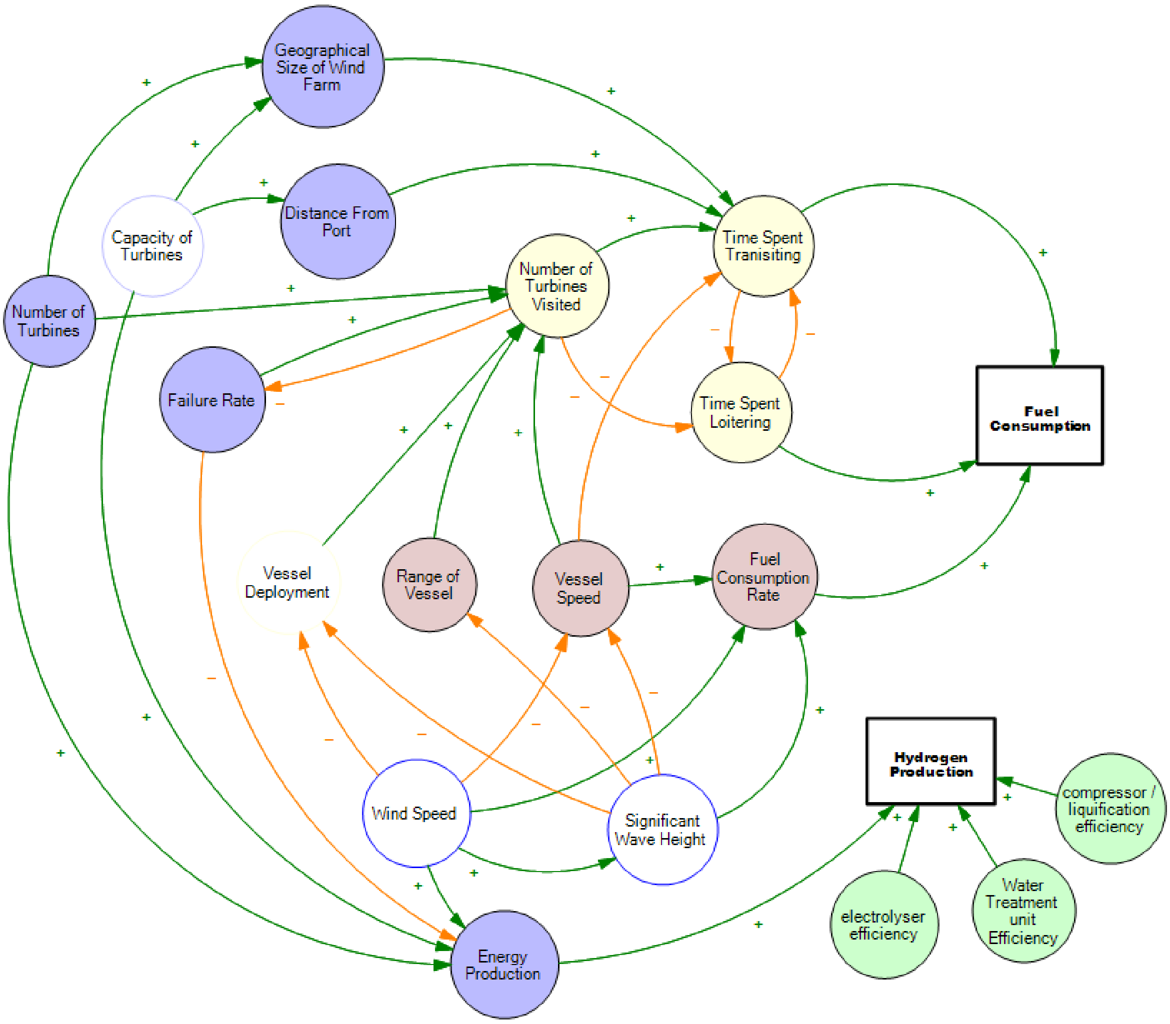


Figure 13: Causal loop diagram for hydrogen demand and production within a wind farm context

By representing the problem from a causal perspective, the various factors could be categorised into features of the; wind farm (Purple), vessels (Pink), O&M activity (Yellow), environment (Blue) and hydrogen production (Green) (Figure 13). From this, the environmental factors were identified as having a complex interaction with the system both increasing annual fuel consumption, via fuel consumption rate, and decreasing via reducing vessel deployment rate, speed, and range. As such these parameters were placed out of scope for the study. Evaluation of the causal diagram allowed the key variables with linear causal interactions to be identified (Figure 13 – filled in variables) and a modelling approach defined (Figure 14). The system diagram in Figure 14 shows the key calculations and processes, indicated by grey boxes, which must be defined in order to address the question under study.

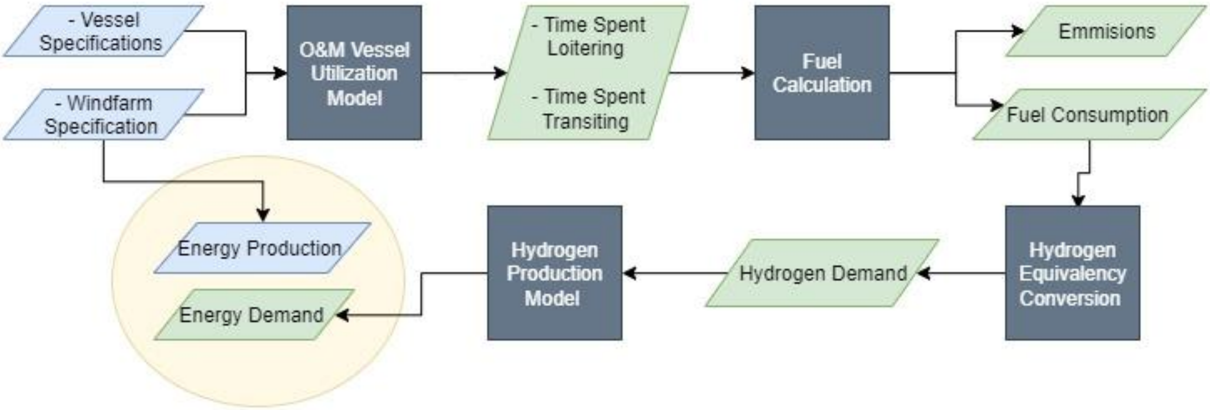


Figure 14: Overview of the system model. Inputs (blue), processes (grey,) and outputs(green)

4.2 O&M Vessel Utilization Model

For the purpose of this investigation a MATLAB based, offshore wind O&M model was created from the ground up, with the key stages described in Figure 15. The model has been given the name MO-VUMA (Maintenance Offshore, Vessel Utilization and Movement Assessment). The MO-VUMA model takes wind farm specifications to model the layout of a turbine array. The model then simulates turbine failure, based on an inputted failure rate, and the deployment and movement of O&M vessels around the windfarm site to visit and repair each failed turbine. By combining this with vessel specification the MO-VUMA model then calculates the distance vessels have travelled and time they have spent loitering on site. Thus MO-VUMA provides a unique O&M model focused on vessel usage.

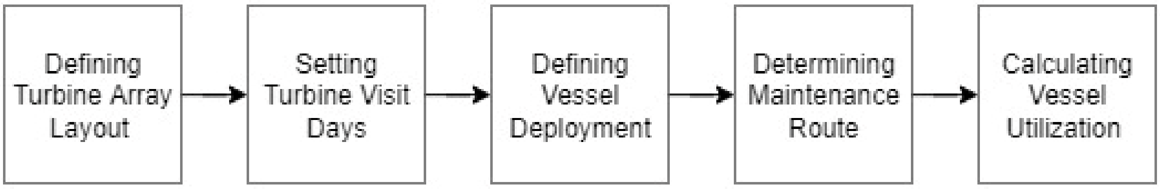


Figure 15: Key stages of the O&M Vessel Utilization Model

The input variables required by the model were selected based of the causal loop analysis (Section 4.1) and are summarised in Table 4, with the model outputs summarised in Table 5. Two case study wind farms are investigated for this study, as such the assumptions made for the value of the input variables are described in section 4.5. In the following sections a detailed explanation of the calculations and MATLAB modelling techniques applied at each key stage of the model are given. An example section of the MO-VUMA code is provided in the appendix.

Table 4: Input Variables Required by the MO-VUMA model

	Input	Units
Wind farm Specifications	Number of Columns	#
	Number of Rows	#
	Column Spacing	km
	Row Spacing	km
	Distance From Port	km
	Turbine Visit Rate	%
	Annual Energy Production	MWh
Vessel Specifications	Vessel Speed	Km/h
	Fuel Consumption Rate – Loitering	L/h
	Fuel Consumption Rate – Transiting	L/h

Table 5: Key outputs of the MO-VUMA model

Output	Unit
Number of Failed Turbines	#
Number of Turbines Visited	#
Distance Travelled by O&M Vessel	Km
Number of Vessel Outings	#
Time Spent Transiting	h
Time Spent loitering	h

4.2.1 Defining Turbine Array Layout

A grid-based structure was assumed for the wind farm layout, taking the column/row number and spacing input values (Defined in Section 4.5). From the grid structure each turbine is assigned an index and x,y coordinate, normalised against the first turbine, as visualised in Figure 16.

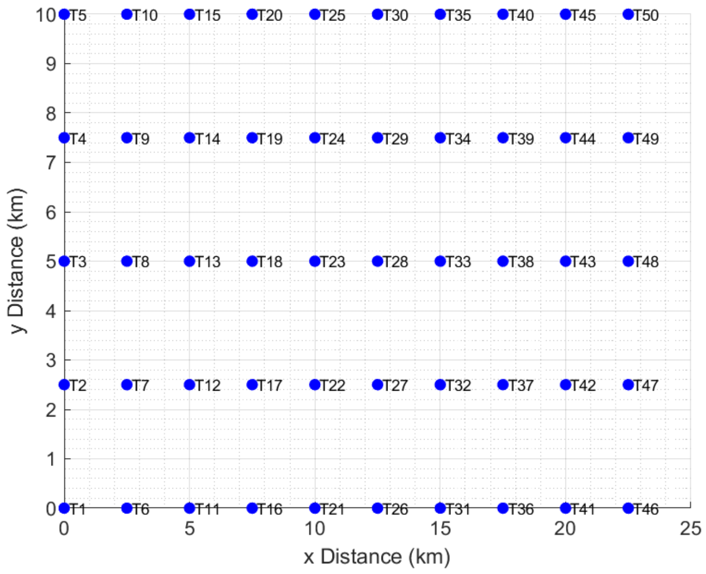
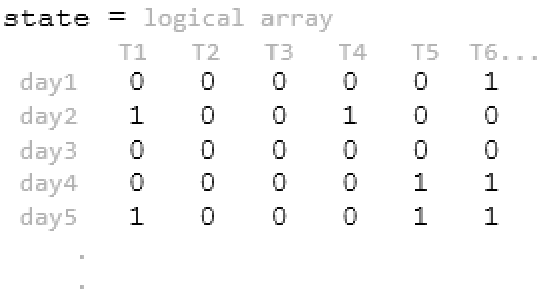


Figure 16: MATLAB visualization of a turbine array defined by the MO-VUMA model

4.2.2 Setting Turbine Failure and Maintenance Visit Days

To model turbine failure a randomised state array was generated whereby columns represent each turbine and rows represent days of the year (Figure 17). On any given day a turbine can either be in an active (0) or failed state and require a maintenance visit (1). For example, in Figure 17, turbine 1 (T1) is in a failed state on day 2 and day 5. The frequency of occurrence of failed states in the randomised array is dictated by the turbine visit rate input parameter. For the final model this was set at 0.052, based on the SPARTA Portfolio Review (2020/21) which states that on average there are 19 vessel visit days per turbine annually[47].



```
state = logical array
        T1   T2   T3   T4   T5   T6...
  day1   0    0    0    0    0    1
  day2   1    0    0    1    0    0
  day3   0    0    0    0    0    0
  day4   0    0    0    0    1    1
  day5   1    0    0    0    1    1
      .
      .
```

Figure 17: Example of a Turbine State Array employed in the MO-VUMA model. (0-Active, 1-Failed)

4.2.3 Vessel Deployment

For each day in the state array (Figure 17) the model first evaluates the array to determine how many turbines are requiring a maintenance visit. It is assumed, for economic efficiency, vessels are only deployed if there are 3 or more turbines requiring a visit [48]. If this is not the case the failed state is rolled over to the next available day in the state array. Additionally, following from the literature review it is assumed that during a single shift a vessel can visit a maximum of 4 turbines [48]. Therefore, for days with more than 4 turbines requiring a visit, additional vessel deployments are modelled as necessary, still taking assumption 1 (Table 6) into account.

Table 6: Summary of Assumptions Applied to Vessel Deployment in the MO-VUMA Model

Assumption	Description
1	A vessel is only deployed if it will visit 3 or more turbines
2	A vessel can visit up to 4 turbines per outing

4.2.4 Maintenance Route

For each day that a vessel is deployed the model assumes the vessel travels from the port to the site origin defined by the array layout (section 4.2.1). The maintenance route the vessel takes is then determined following a nearest neighbour principle. Firstly, the distance from the vessel to each turbine in a failed (1) state is evaluated using the Euclidean distance equation (Equation 1).

$$Distance(v,t) = \sqrt{(x_t - x_v)^2 + (y_t - y_v)^2} \qquad (Equation\ 1)$$

Where:

v – Vessel

t- Turbine

The closest turbine is selected, its state changed to ‘0’, the vessel position updated to the coordinate of the selected turbine and the distance recorded. This process is repeated until the vessel has visited its maximum number of turbines (defined in section 4.2.3). The maintenance route distance is added to the port-site and return journey distance to give the final distance travelled by the vessel on that day. The process is repeated for any additional vessel deployments required until vessel deployment assumption 1 is reached (Section 4.2.3, Table 3). The number of vessels deployed, number of turbines visited and total cumulative distance on a given day is recorded. An example route mapping, of a multi vessel day, resulting from this methodology is described graphically in Figure 18. For additional optimization the nearest neighbour priority is given in reverse turbine order. For example, in Figure 18, T39 and T49 are equal distance from T43 but the vessel will move to T49.

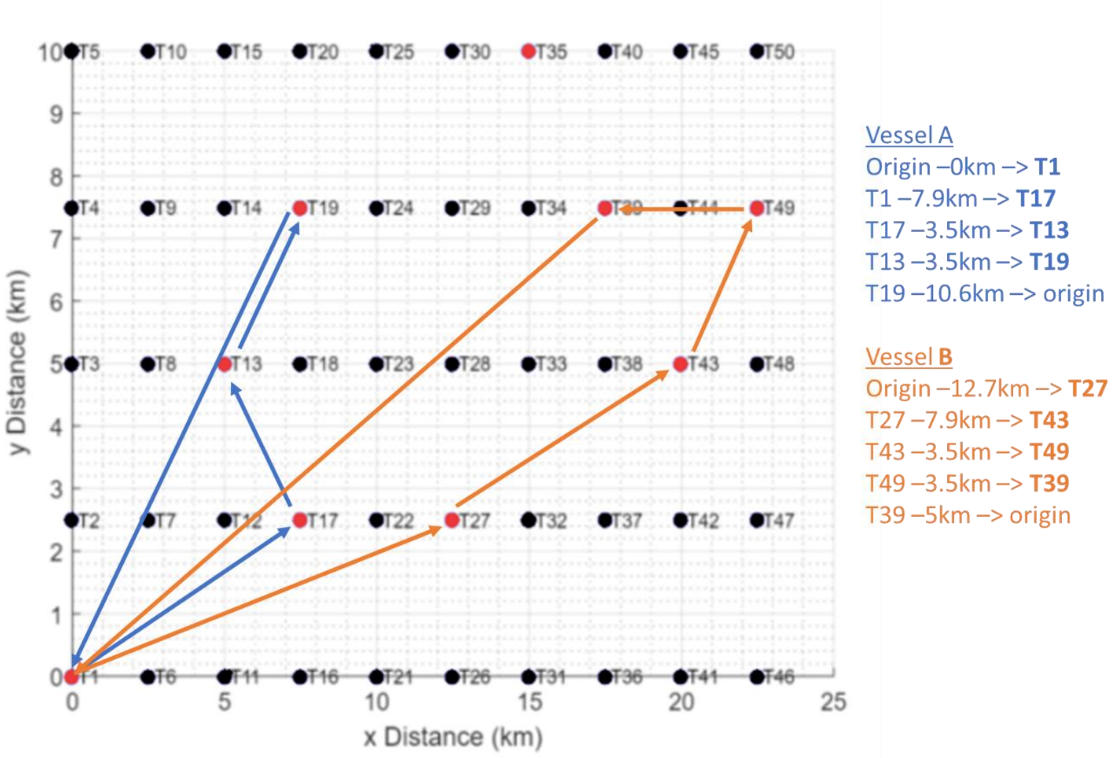


Figure 18: Visualization of how the MO-VUMA model maps maintenance routes following the nearest neighbour principle.

4.2.5 Vessel Utilization

Vessel Utilization is defined as the amount of time spent transiting and loitering. The time spent transiting is calculated from the distance travelled assuming the vessel travels at a constant speed (equation 2). The vessel speed is set by the vessel speed input value, which is defined for each case study scenario in section 4.5. It should be recognised that vessels will travel at slow speeds in harsh weather conditions effecting the overall time spent transiting.

However, the effects of weather conditions were placed out of scope of this model, as explained in section 4.1.

$$Time\ Transiting\ = distance\ travel\ /\ vessel\ speed \qquad \text{(Equation 2)}$$

A 12-hour shift pattern is common for CTV deployment on wind farms [48]. Therefore, it is assumed that any time not spent transiting, during the 12-hour shift, the vessel will be loitering in field. As such the time spent loitering is calculated following equation 3.

$$Time\ Loitering\ = (shift\ length\ \times number\ of\ vessels\ deployed) - Time\ Transiting \qquad \text{(Equation 3)}$$

4.3 Fuel Consumption and Emissions

Many parameters affect fuel consumption rate, such as weather and sea conditions, weight of the vessel, speed of vessel and engine efficiency as explored in section 4.1. For this study a simplification was made, assuming the vessel has a constant weight and speed and is unaffected by weather conditions. The variation in fuel consumption rate depending on activity (loitering or transiting) was considered. The values assumed here (Table 7) are based on the manufacture specification for the Windcat MK4 CTV, a common CTV found in North Sea Offshore Wind developments [49], [50]. The time spent loitering and transiting (vessel utilization) calculated by the MO-VUMA model were combined with these fuel consumption rates (Table 7) to estimate the total fuel consumption, following Equation 4.

$$Fuel\ Consumption\ (L/h) = Duration\ of\ Activity * Fuel\ Consumption\ rate\ of\ Activity \qquad \text{(Equation 4)}$$

Table 7: Summary of Fuel Consumption and Emissions Model

Input	Unit
Time Spent Transiting	h
Time Spent Loitering	h
Site Annual Energy Production	GWh

Model Parameters	Unit	Value
Fuel Consumption Rate – Transiting (L/h)	L/h	310
Fuel Consumption Rate – Loitering (L/h)	L/h	120
MGO Emissions Factor (kg CO2e per L)	kg CO2e per L	2.775

Output	Unit
Fuel Consumption	L
Emissions	kg CO2e
	kg CO2e/GWh

The significance of decarbonising vessels is due to the global warming impact associated with emissions produced by burning current marine fuels. As such an additional calculation was performed to evaluate the equivalent CO2 emissions produced by the O&M vessel activity simulated by this model. A MGO fuel emission factor of 2.775 kgCOe/L was assumed (Table 7) based off the 2021 fuel emission factors published by the UK Government department for Business Energy and Industrial Strategy[51]. This was applied to the calculated fuel consumption to estimate carbon emissions from the O&M vessels, following Equation 5.

$$Carbon\ Emmisions\ (\mathrm{Kg\ CO2e}) = Fuel\ Emiisions\ Factor * Fuel\ Consumption \quad \textit{(Equation 5)}$$

4.4 Hydrogen Model

To evaluate the feasibility of fuelling O&M vessel with hydrogen produced from wind powered electrolysis, the hydrogen fuel demand and energy for hydrogen production was calculated.

4.4.1 Hydrogen Demand

The estimated marine fuel consumption (Section 4.3) was used to predict the equivalent hydrogen demand for the vessels. This was achieved following the approach presented by Grey *et al* [6]. Firstly, the energy content of the marine fuel, and the corresponding energy used for propulsion by burning the fuel was determined. This was achieved using Equation 6 which takes into consideration the efficiency of the combustion engine (Table 8). From this the equivalent energy required for propulsion through hydrogen is determined, taken into account the efficiency of a hydrogen fuel cell (Equation 7). The final hydrogen demand, by mass, is thus determined using the lower heating value of hydrogen (Equation 8). It is important to consider that the corresponding volume of hydrogen fuel, and thus sizing of a vessels fuel tank, is dependent on whether it the hydrogen is stored in a gaseous or liquid state. The volumes were calculated, following Equation 9, using the fuel properties of hydrogen (Table 8).

$$E_{mf} = V_{mf} U_{mf} \eta_{ce} \quad \textit{(Equation 6)}$$

$$E_{H2} = \frac{E_{mf}}{\eta_{fc}} \quad \textit{(Equation 7)}$$

$$M_{H2} = \frac{E_{H2}}{LHV_{H2}} \quad \textit{(Equation 8)}$$

$$V_{H2} = \frac{M_{H2}}{\rho} \quad \textit{(Equation 9)}$$

Where:

E – Energy used for propulsion (MJ)

V – *Volume (L)*

M – *Mass (kg)*

η – *Efficiency (%)*

U – *Energy Density (MJ/L)*

LHV – *Lower heating value (MJ/kg)*

ρ – *Density (kg/L)*

mf −*Marine Fuel*

$H2$− *Hydrogen*

ce− *Combustion Engine*

fc− *Hydrogen Fuel cell*

Table 8: Fuel Properties (source [52])

Fuel	Density ρ (kg/L)	Energy Density U (MJ/L)	Heating Value LHV (MJ/kg)	Engine Efficiency η (%)
Marine Gas Oil	0.860	38	43	45
Hydrogen Gas (500 bar)	0.033	8.28	120	50
Hydrogen Liquid (-253C)	0.070	3.96	120	50

4.4.2 Hydrogen Production

Following the method proposed by Bonacina *et al* [53] the energy required to produce hydrogen was assessed considering each component of the hydrogen production system as described by Figure 19. For this study a PEM type electrolyser was chosen due to its production flexibility and suitability to the variable energy supply associated with wind energy, as discussed in section 2.3.2.

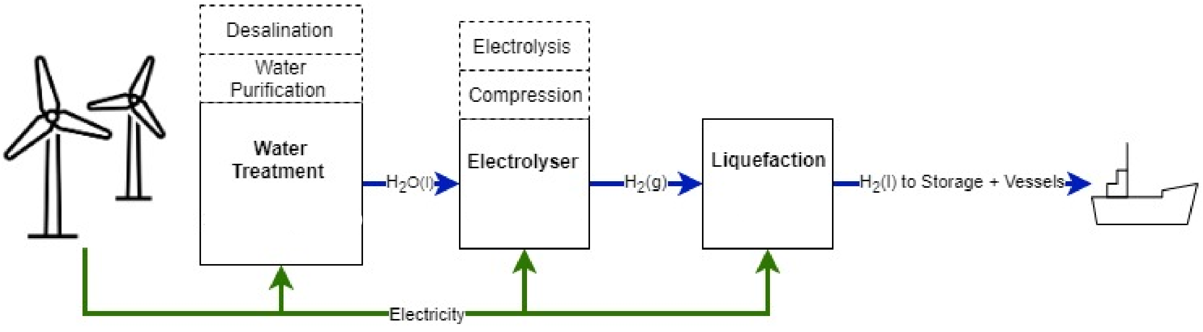


Figure 19: Schematic of liquid hydrogen production utilizing wind energy (Adapted from Bonacina et al 2022 [53])

Due to the available literature data the process was simplified into water purification (including desalination and demineralisation), Electrolysis (including compression) and liquefaction (Figure 19). The assumed values for each stage, based on the literature review, are given in Table 9. As such, the overall energy required to produce a kg of liquid hydrogen is given by Equation 10. It is assumed the energy required to produce a kg of gaseous hydrogen can be found by removing the energy consumption of liquefaction. In reality there will be some variation due to the difference in equipment efficiency and pressures required. However, this simplification reflects the uncertainty in the available literature, and deemed to still provide a good estimate of energy demand.

Table 9: Performance indicators of Hydrogen production components

System Component	Energy Consumption (kWh/kg)	References
Water Treatment	4	[37], [53], [54]
PEM Electrolysis	50	[37], [38], [45], [53]–[55]
Liquefaction	6	[40], [53], [56]

$$\boldsymbol{E_{H2} = (E_{WT} + E_{EL} + E_{LP})(1 + \eta_{AUX})} \qquad \textit{(Equation 10)}$$

Where:

E_{H2} – *Total energy consumption per unit mass of hydrogen produced*

E_{WT} – *Energy consumption for water treatment*

E_{EL} – *Energy consumption for Electrolysis*

E_{LP} – *Energy consumption for Liquefaction*

η_{AUX} – *Efficiency accounting for Auxiliary losses*

The wind energy required to produce enough hydrogen to power the O&M vessels is thus obtained by multiplying hydrogen demand (section 4.4.1) by the total energy consumption of the hydrogen production system (Equation 11). One limitation of this method is that load efficiencies and component capacities are not considered.

$$E = M_{H2}\, E_{H2} \qquad \textit{(Equation 11)}$$

4.5 Scenario Selection

To explore the capability of the MO-VUMA model and gain insights towards the feasibility of decarbonising offshore service vessels utilizing hydrogen production from wind curtailment, two case study scenarios were simulated. The assumed values for the model inputs for each scenario are given in Table 10.

4.5.1 Scenario 1 – Verification

As part of the study 'Setting A Benchmark for Decarbonising O&M Vessels of Offshore Wind Farms' ORE Catapult used their own internal O&M simulation tool, COMPASS, to model a hypothetical windfarm [48]. The scenario presented in their paper represents a near-shore windfarm consisting of 50 turbines and an O&M strategy based on CTVs only. A full list of the windfarm and vessel parameters assume in their study are detailed in Table 10, scenario 1. These were replicated exactly and simulated in the MO-VUMA model in order to compare and verify the distance and vessel utilization calculated by the methodology developed for MO-VUMA, with those predicted by the ORE COMPASS tool.

4.5.2 Scenario 2 – Humber Gateway

The Port of Grimsby is home to the National Clean Maritime Demonstration Hub [57]–[59], as well as the OYSTER and Gigastack Offshore Wind to Hydrogen projects [60]–[62], and the ORE Catapult's O&M Centre of Excellence[63]. As such it was identified as a particular area of interest for this study. The Humber Gateway wind farm is situated 8 km off the Holderness coast and the O&M for the site is based out of the Port of Grimsby [64]. Therefore, the Humber Gateway was chosen as a case study wind farm to model, with high relevance to current work in the field vessel decarbonisation and wind to hydrogen.

The Humber Gateway consists of 73, Vastas V112, 3 MW turbines, covering an area of approximately 25 square kilometres [64]. Therefore, a column and row spacing of 3 and 3.5 km was assumed, to achieve a 25 km^2 site. Due to the nature of the MO-VUMA model placing turbines on a m by n grid array the simulation only considers 72, rather than 73 turbines. This small deviation is deemed to have a negligible effect on the predicted results. A full list of the parameters and assumptions applied to the model to simulate the Humber Gateway are provided in Table 10. A review of vessels using marineTraffic.com showed that WindCat CTVs are commonly found around UK wind farms. As such a Windcat MK4 was taken as a reference vessel for this study. It should be noted that turbine visit rate of 0.052 and vessel speed of 48.2 km/h has been assumed, which differs from the scenario 1 simulation. These values were chosen as they represent the most up to date literature [47], [50].

Table 10: Case Study simulation, model input parameters

	Parameter	**Scenario 1** [48]	**Scenario 2** [47], [50], [64]
Windfarm Specification	Number of Turbines	50	72
	Number of Columns	10	9
	Number of Rows	5	8
	Column Spacing (km)	2.5	3
	Row Spacing (km)	2.5	3.5
	Distance From Port (km)	20	8
	Turbine Visit Rate (% of days a year)	0.089	0.052
	Annual Energy Production (MWh)	568,826	803,000
Vessel Specifications	Vessel type	CTV	CTV
	Transit Speed (km/h)	42.6	48.2

	Fuel Consumption Rate - Loitering (L/h)	130	130
	Fuel Consumption Rate - Transiting (L/h)	320	320

5.0 Results and Discussion

The first objective of this study was to develop a new tool (MO-VUMA) to address the research gap in modelling offshore wind O&M vessel usage, fuel consumption and emissions. The aim was for the tool to have future applicability to LCA analysis as well as evaluating fuel demands of O&M vessels for study into implementation of alternative fuels. Therefore, section 5.1 of the results discussion focuses on verification and analysis of the model itself. Secondly, the MO-VUMA and hydrogen model was applied to the Humber Gateway case study and the results are discussed in section 5.2.

5.1 MO-VUMA Methodology Verification and Analysis

The purpose of scenario 1 simulation was to validate how the methodology developed for the MO-VUMA model evaluates vessel usage during O&M activities by comparing with the results reported from the ORE Catapult COMPASS tool [48], using the same windfarm and vessel specifications. A summary of the findings are presented in Table 11. Initial analysis showed agreement between the two models in the ratio of time spent transiting compared to loitering in field (Figure 20). However, the results reported by ORE catapult for total distance travelled and vessel utilization over one year were 22,493 km and 4,295 h respectively. Whereas the MO-VUMA model calculated an annual distance of 31,095 km and 5,028 hours of vessel utilization (Table 11). Therefore, to evaluate the cause of differences in the final distance and utilization, the outputs of the model were explored further.

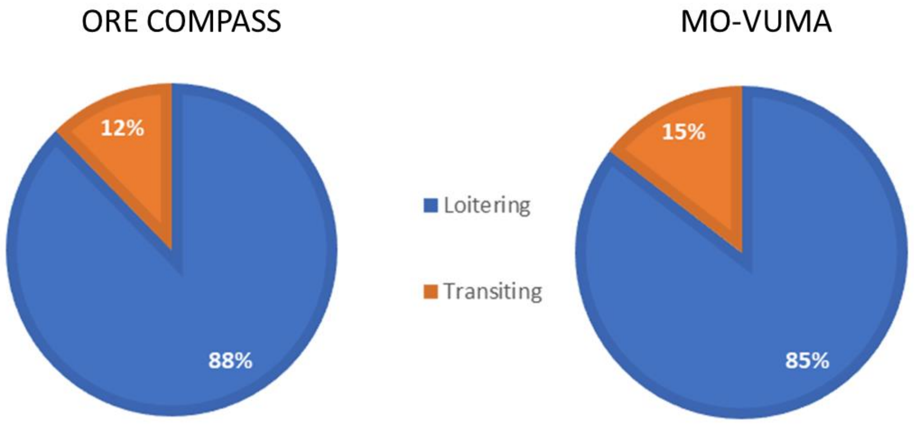


Figure 20:Percentage of time spent loitering and transiting predicted for scenario 1

Table 11: Summary of Results Calculated for Scenario 1 by MO-VUMA, compared with ORE Catapult reference case.

	ORE COMPASS [48]	***MO-VUMA***	***Percentage Difference***
Transit Distance (km)	22,493	31,095	+38%
Vessel utilization (h)	4,295	5,028	+17%
Fuel Consumption (L)	256,276	792,326	+209 %
CO2e (tonnes)	2,048	2,462	+20%
CO2e (tonnes per MWh)	0.0036	0.0043	+19 %

To investigate the discrepancy the vessel utilization was broken down by hours per activity as shown in Figure 21. This analysis found only 2% difference in time spent transiting between port calculated by each model, suggesting the models have agreement on the number for vessel outings required to fulfil the O&M activities. Similarly, the results show only 15% difference in the predictions of time spent loitering in field (Figure 21), providing confidence in the methodology used to model vessel deployment and loitering. However, from this analysis a significant difference of 134% in time spent transiting between turbines, calculated by the two models was identified (Figure 21). Consequently, it was concluded that the maintenance route (transiting between turbines) stage of the simulation is the significant aspect of the model that is contributing to overall differences seen in the results for annual distance travelled and vessel utilization.

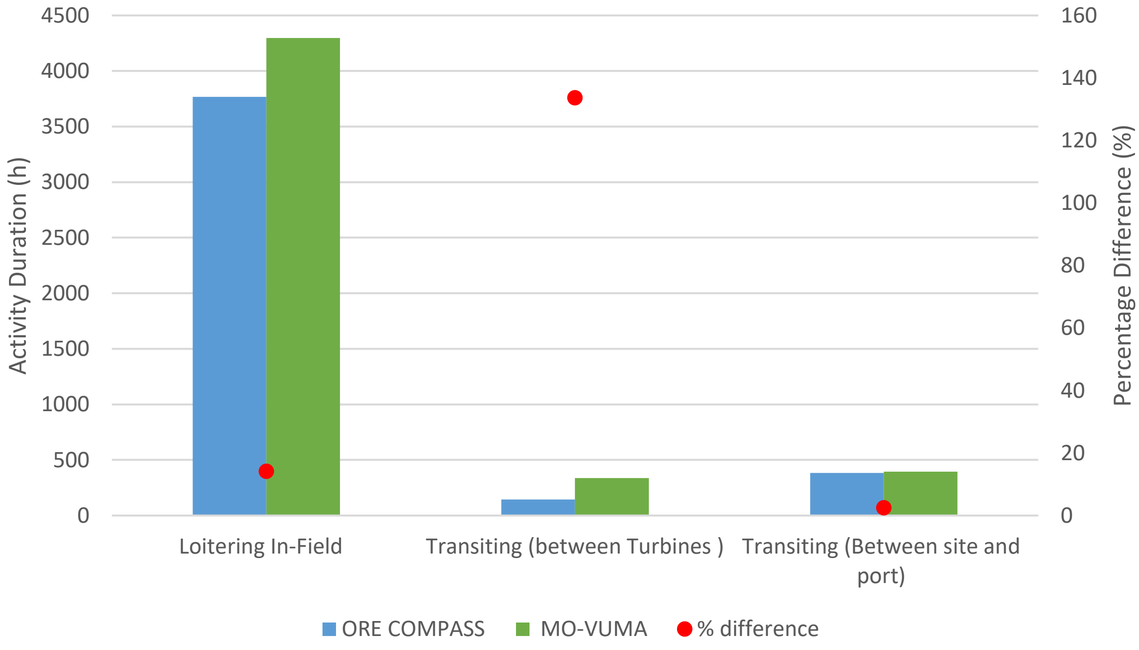


Figure 21: Annual vessel usage, by activity, predicted for scenario 1

Most significantly a 209% difference in the predicted fuel consumption was found. Transiting fuel consumption rate (320 L/h) is higher than loitering (120 L/h). Therefore, total fuel consumption has a high sensitivity to time spent transiting, despite this activity making up a small proportional of the overall vessel usage time. As such, the difference in the turbine-

turbine transiting calculations of the models, discussed previously, explains the large contrast in annual fuel consumption predictions (Table 11).

Referring to the report published by ORE catapult it was found that the methodology used in their modelling assumed, once a vessel had reached the site, an extra 15km would be travelled to drop off/pick up technicians for the complete journey to four turbines [48]. This indicates that all turbines visited are assumed to be adjacent in their simulation. While this may be the case for planned or scheduled maintenance activities, it is unlikely for unplanned maintenance where failed turbines will be spread widely across the site. Notably, ORE Catapult report also showed more vessel time was used for unplanned than planned turbine maintenance [48]. It is therefore believed, the MO-VUMA model developed for this study provides an advanced representation of turbine-to-turbine transiting, due to the randomization of failure across the wind turbine array. Accordingly, it is concluded that the high values for turbine-to-turbine transit time and annual fuel consumption calculated by the MO-VUMA model, provides the closer estimation to the expected value.

For further verification it would have been desirable to compare route modelling and vessel utilization with other O&M simulation tools, such as the verification methodology presented by Dinwoode *et al* [33]. However, as stated in the literature review (Section 2.2.1) the focus of most O&M simulation tools is on predicting and optimizing O&M costs and site availability. Prior studies have not explored vessel movements and according to the author's search relevant literature on vessel utilisation could not be found. However, emissions associated with O&M activities are often reported in life cycle assessments or by the wind farm operators themselves [24], [26], [48], [65], [66]. An additional verification was therefore considered utilizing the fuel consumption, and associated emissions, resulting from the vessel utilization (Figure 22).

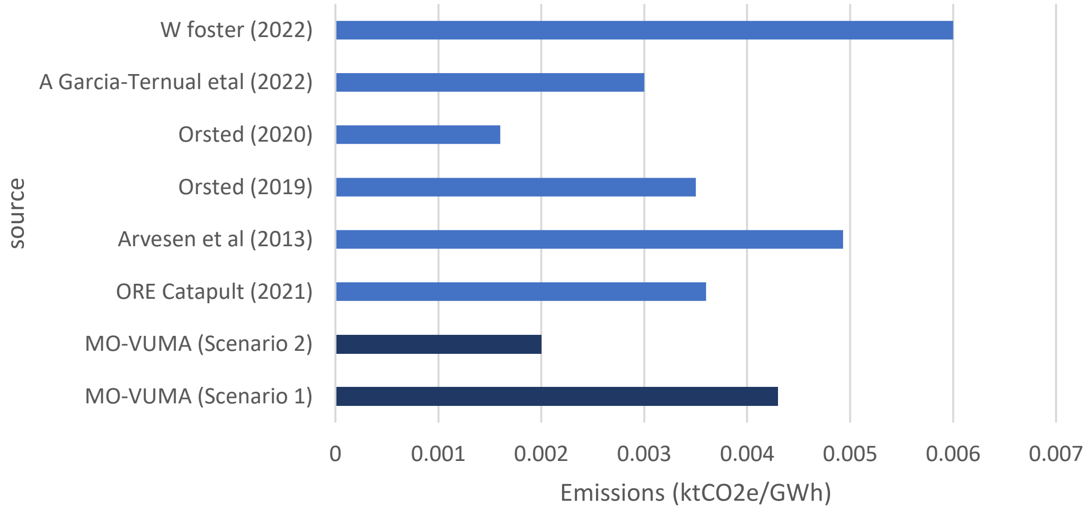


Figure 22: O&M vessel emissions compared to literature data [24], [26], [48], [65], [66]

Variation in the emissions values reported in literature are expected as they represent wind farms of various size and distance from port. Despite this the comparison shows that the results from the MO-VUMA model sit in the expected range. Additionally, the results from scenario 2 simulation have been included in this comparison (Figure 22). The scenario 2 simulation used differing values for turbine visit rate and vessel speed to reflect the most up to date data from the SPARTA Review. It can be seen that the results from this align with the most up to date emissions statistics from Orsted (2020) (Figure 22). This indicates that the MO-VUMA tool can accurately calculate vessel fuel usage and emissions, which offers value for LCA in the offshore wind sector.

5.1.1 Assumptions and Limitations

With the application of any modelling tool, it is important to recognise the assumptions and limitations of the model. Four key assumptions (section 5.1.1.1 – 5.1.1.2) and limitations (section 5.1.1.3 – 5.1.1.4) of the MO-VUMA model were identified, and the implications and significance of these are discussed below.

5.1.1.1 Array Layout

As described in section 4.2.1, a simplification was made assuming the turbine array takes the form of evenly spaced placements on a grid layout. In practice turbines are commonly placed offset to each other to reduce wake effects that impede energy production [67]. This can be seen in the Humber Gateway site map provided by RWE (Figure 23, left)[64]. A visualization of the layout assumed by the MO-VUMA model is shown in Figure 23 for comparison. Although both layouts have 3 km spacing between turbine rows, the difference in alignment of the columns will mean the calculated distance between turbines by the model will vary from the true value. Relative to overall distances the deviation will be small and therefore acceptable for the purpose of this study. However, this limitation will have a higher contribution to daily distances travelled as the number of journeys and size of wind farm modelled is increased. This can be corrected and accounted for in future model improvements by adding an offsetting factor to the turbine array layout scrip. Additionally, MATLAB has a function that maps points of latitude and longitude. Should more precise distance calculations be required a suggested improvement would be to utilize this function with turbine latitude and longitude data occasionally available from the wind farm operators[68].

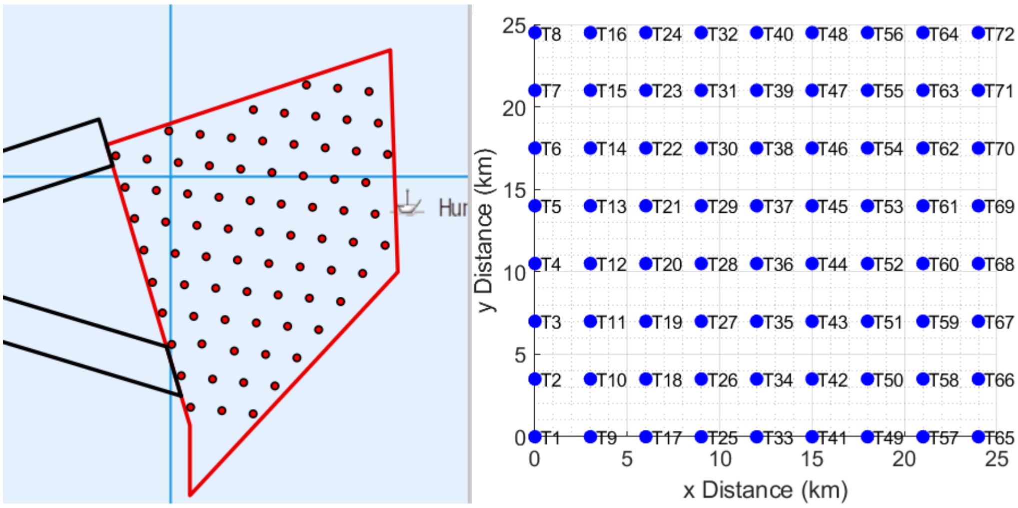


Figure 23: Humber Gateway Wind Farm layout depicted by the published site map (left)[64]*, and MO-VUMA model representation (right)*

5.1.1.2 Vessel Route and Optimizations

The overall distance travelled, and thus vessel utilization and fuel consumption, is affected by the route a vessel takes. For ease of calculation the model considers 3 degrees of movement (along x, y and xy vectors). In practice, routes taken by the vessels are likely to be unique to each wind farms local geography and operating procedures. To put this assumption into context an example of actual vessel movement around the Humber gateway, derived from AIS data of the vessel WINDCAT 1 (MSI: 235018872), is presented in Figure 24. It must be noted that this track is from an unknown timeframe but illustrates the movement of a CTV vessel. This assumption is not expected to have a significant effect on the overall results predicted by the model. However, real time vessel movements can be monitored from AIS data available from sites such as marinetraffic.com [69] Future studies could consider combining this data to provide better understanding of vessel movement and influence future modelling work. This was placed out of scope for the present study.

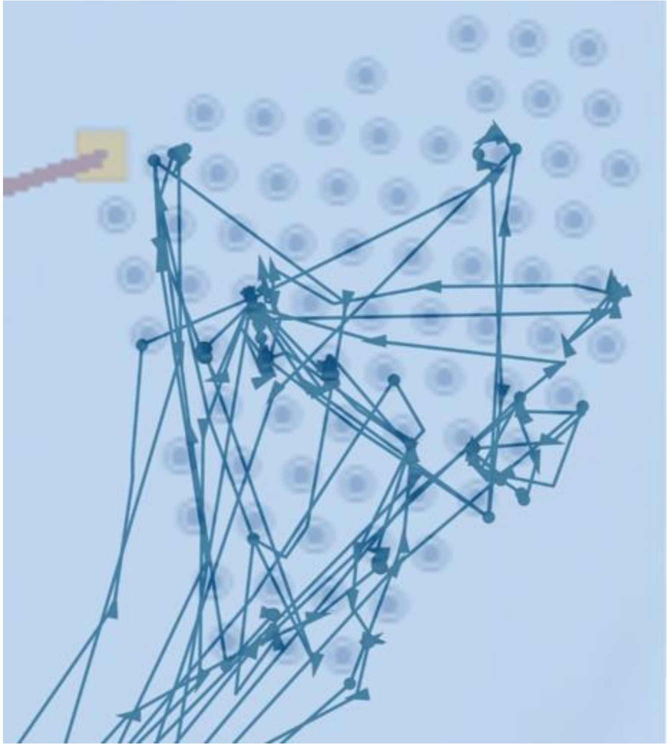


Figure 24: Overlay of AIS data of CTV vessel tracks around the Humber Gateway wind farm. Adapted from marinetraffic.com [69] *and 4COffshore* [70].

5.1.1.3 Variance

The MO-VUMA methodology is statistical in nature, with the failure of turbines randomised across the entire array. Due to this there is expected variance in the vessel transit results predicted from the model each time it is run. To explore this, the scenario 1 simulation was repeated 500 times and the total annual distance travelled recorded. Distance travelled was selected as the measured variable as it is most directly affected by the randomisation, and due to the high sensitivity of total fuel consumption to this variable as identified previously (Section 5.1). A histogram of the results can be seen in Figure 25. It was found that the predictions for annual distance travel ranged from 29,000-33,500 km with a mean of 31,095 km and a standard deviation of 690.

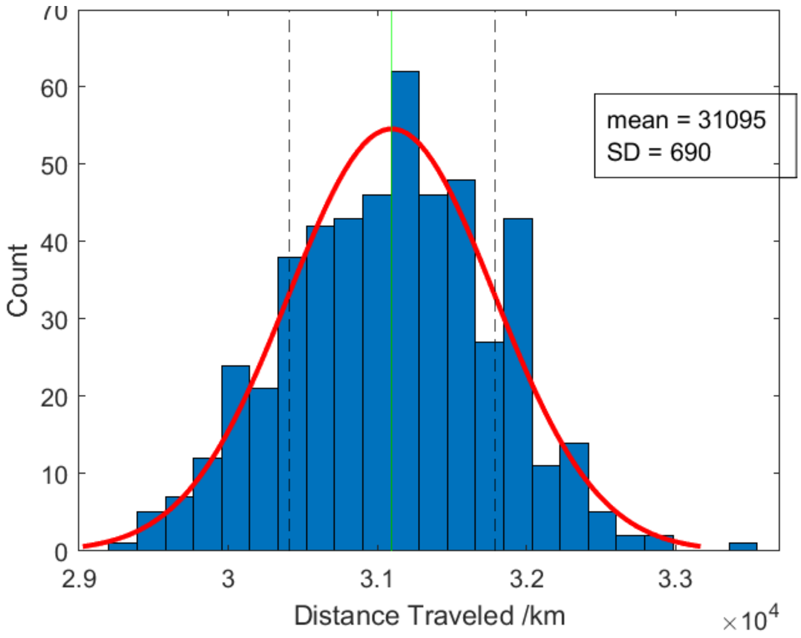


Figure 25: Variation in total distance travelled output, over 500 runs of scenario 1 simulated by MO-VUMA.

These results demonstrate a considerable variance, which is expected to be proportional to the number of turbines considered by the model, due to the number of possible failure combinations. This factor must be understood and acknowledged during results interpretations. However, this variance may also be representative of the unpredictable nature of turbine failure, and year to year variation observed at operational wind farms and thus considered acceptable for the purpose of the study.

5.1.1.4 Seasonal Variation

The daily distances travelled by vessels calculated by the MO-VUMA simulation of scenario 1 are shown in Figure 26. The results suggest relatively even distribution and consistent travel distance throughout the year. However, as discussed in section 4.1, vessel deployment is subjective to weather and sea conditions and as such a seasonal variation in number of vessel outings and consequently distance covered per day would be expected. The MO-VUMA model does indicate a relationship of 71 km per vessel outing. Despite the limitation of the MO-VUMA model at deriving distances to a seasonal resolution, the results do give an average of 19 vessel visits per turbine per year in line with that reported by the industry. Although the model shows these visits occurring uniformly across the year the resulting total annual distance is unaffected.

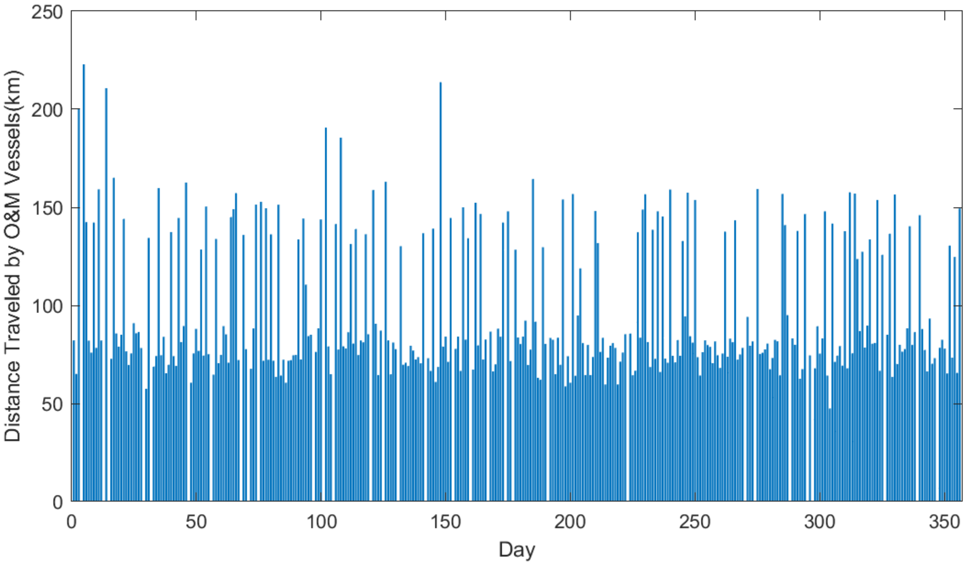


Figure 26: Daily distances travelled by O&M vessels calculated by MO-VUMA for scenario 1

5.2 Humber Gateway Case Study

The verification analysis demonstrates that the MO-VUMA model does provide a suitable estimation of vessel usage and fuel consumption, despite the limitations discussed above. As such, the model was applied to simulate O&M of the Humber Gateway windfarm to measure vessel usage and fuel demands. These results were in tern used with the hydrogen module to calculate and analyse hydrogen demand and the feasibility of meeting this with onsite wind powered hydrogen production.

5.2.1 Vessel Usage and Fuel Consumption

The MO-VUMA simulation of the Humber Gateway wind farm calculated the total annual distance travelled by O&M vessels to be 23,995 km, 5440 km of which are attributed to port to site travel and 18,555 for turbine-to-turbine travel. From the results a relationship of 100 km per vessel outing was found which aligns with the study conducted by A.Łebkowski (2020) that calculated that CTVs can run a daily route up to 180km[71]. The results again give a ratio between time spent loitering (12%) and time transiting (88%) in agreement with the study conducted by ORE Catapult[48]. The resulting annual duration of vessel deployment, by activity type, and corresponding fuel consumption outputted by the MO-VUMA simulation is shown in Figure 27.

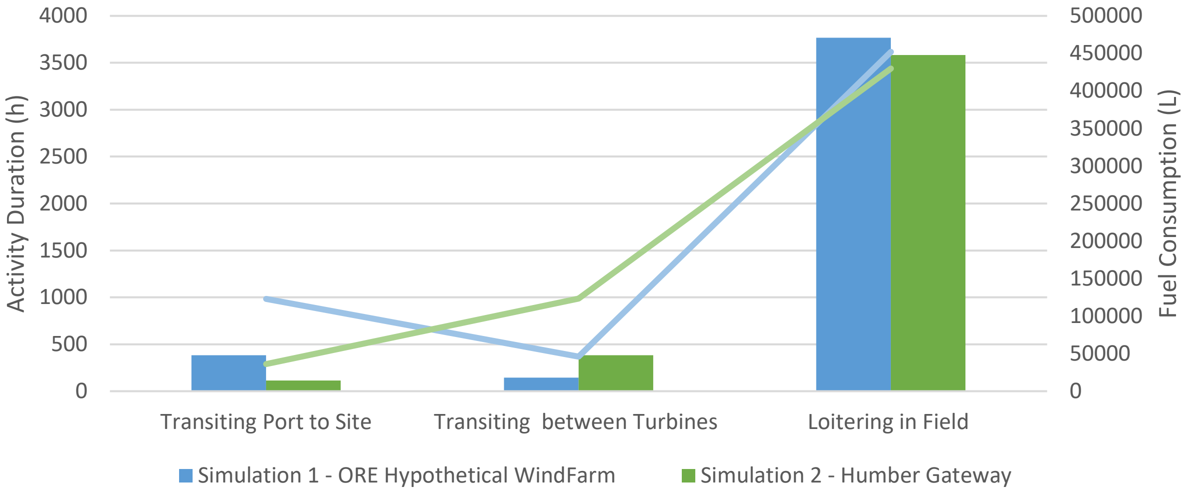


Figure 27: Annual Vessel Utilization (Bar) and Fuel consumption (Line), per activity

It can be seen from the results of the Humber Gateway simulation that the smallest proportion of deployment time is attributed to transiting from port to site, at only 113 hours (2.8%). This contrasts with the hypothetical wind farm simulation (simulation 1) that found the smallest proportion of deployment time attributed to transiting between turbines (Figure 27). This result is expected and can be explained by the difference in the distance of each windfarm is from port. The Humber Gateway wind farm is a near shore site situated just 8km from the Grimsby O&M hub, where is the site modelled for simulation 1 is representative of more recent developments at 20 km from port. This result demonstrates the sensitivity of vessel transiting times with less time available for transiting between turbines for O&M of sites further form port. Interestingly the simulation results indicate the majority of vessel deployment time is spent loitering in field irrespective of distance from port. It can be concluded from this that despite fuel consumption rates of vessels being highest when transiting, most of the fuel usage during a vessel outing will occur from loitering. This can be seen in fuel consumption and emissions results from the Humber Gateway simulation, shown in Figure 28. As such, it is recommended that technology used to maintain vessel position when idle in field should be a focus of efficiency improvements to reduce vessel fuelling demands.

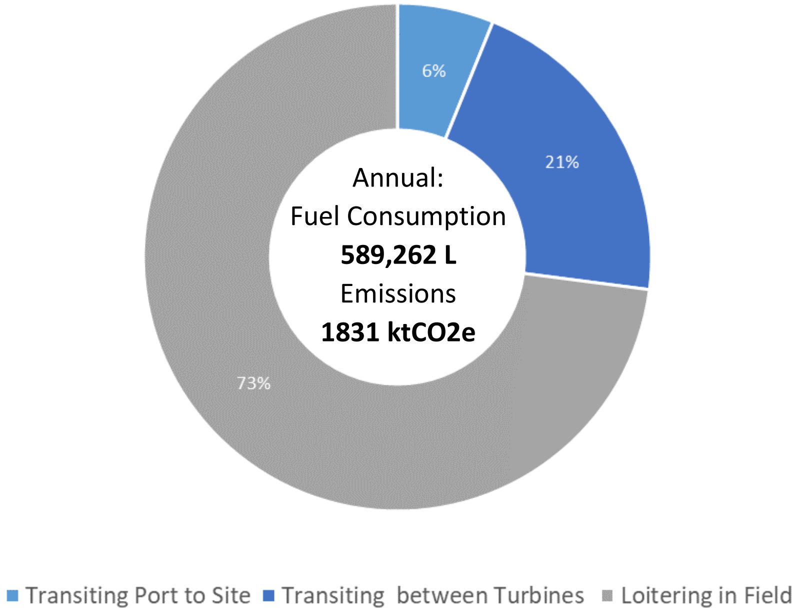


Figure 28: Summary of Fuel Consumption and Associated Emissions from O&M of the Humber Gateway Wind Farm

The results from the MO-VUMA simulation of the Humber Gateway wind farm calculated the expected annual fuel consumption of the O&M vessels to be 589, 262 L (Figure 28). The emissions produced from the combustion of this volume of marine fuel equate to 1831 ktCO2e. This gives the O&M of the windfarm site an emissions contribution of 0.002 ktCO2e per GWh, which aligns with the average value expected from wind farm O&M as reported by Orsted (2020) and discussed in section 5.1 (Figure 17).

5.2.2 Hydrogen Fuelling Analysis

5.2.2.1 Energy Demands

The hydrogen model, described by section 4.4, was used to convert the MGO fuel consumption results from the MO-VUMA simulation into an equivalent hydrogen demand for fuelling the O&M vessels. It was calculated that to supply the equivalent propulsion energy utilizing hydrogen as a fuel, 2428151 kg H_2 would be required annually. A summary of the results from the hydrogen model, showing energy needed to produce this required mass of hydrogen in the gaseous and liquid forms, along with the percentage of annual production of the Humber Gateway windfarm, are given in Table 12.

Table 12: Summary of hydrogen fuelling requirements to meet the annual demand from the Humber Gateway O&M vessels

Hydrogen Sate	Required Volume (L)	Energy for Hydrogen Production (MWh)	Percentage of Humber Gateway Annual Energy Production
Gas, 500 bar	73,580,322	131,120	16.3 %
Liquid, -253C	34,687,866	145,689	18.1 %

The results in Table 12 show that to produce clean fuel to meet the demands of O&M vessels, 16-18% of the annual energy production of the site would need to be diverted to hydrogen production. This is a promising result as it indicates that it is achievable to supply the energy demand of O&M vessel via on-site hydrogen production, negating the need to import hydrogen from other sources. Additionally, the percentage of annual energy production required falls within the average curtailment levels of UK windfarms (14-22%) [41]. As such the results from this study further evidences the feasibility of alleviating current curtailment issue by utilising the energy for hydrogen production to fuel maintenance vessels.

For the windfarm site itself the average daily hydrogen demand was found to be 6828 kg, requiring 375 MWh of energy to be diverted for hydrogen production. Therefore, it would be recommended that the site has a hydrogen production system with a 15.6 MW capacity. However, as would be expected the daily demand varies significantly depending on the number of turbines visited and vessels deployed. This relationship is as shown in Figure 29. A jump in distance travelled and hydrogen demand is seen between 4-7 and 8-11 turbines visits per day, due to additional vessel deployments and the assumption that a single vessel will only visit 3-4 turbines per outing. The frequency of occurrence of 0,1,2 and 3 vessel deployment days is illustrated in Figure 30, along with the corresponding energy required for hydrogen production to meet the daily fuel demand. The results illustrate that sizing of an electrolyser can be based of vessel deployment strategy.

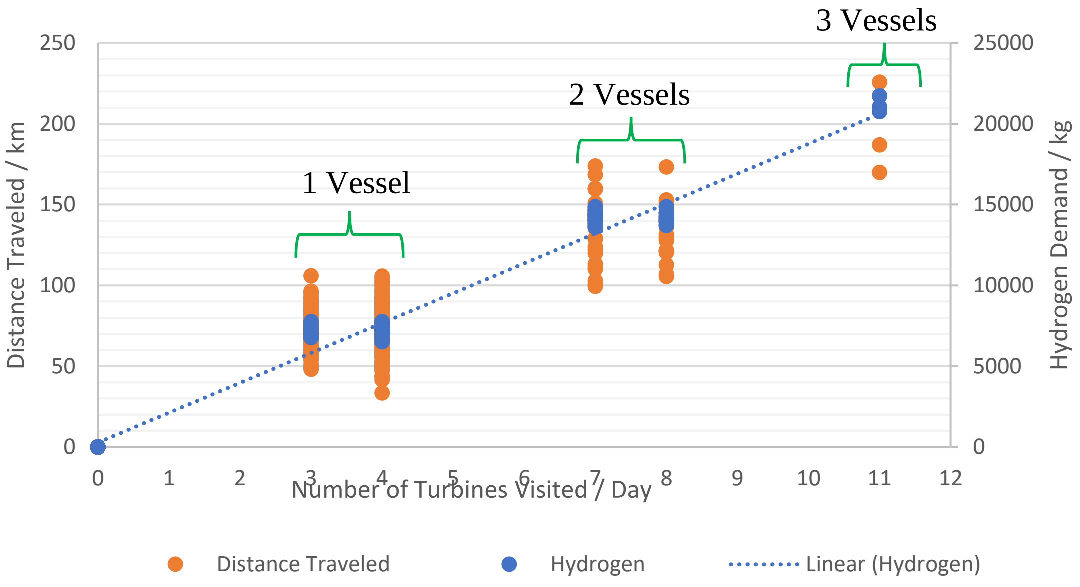


Figure 29: Relationship between in daily number of turbines visit, distance travelled and hydrogen fuel demand. Predicted for the Humber Gateway O&M activities using the MO-VUMA model.

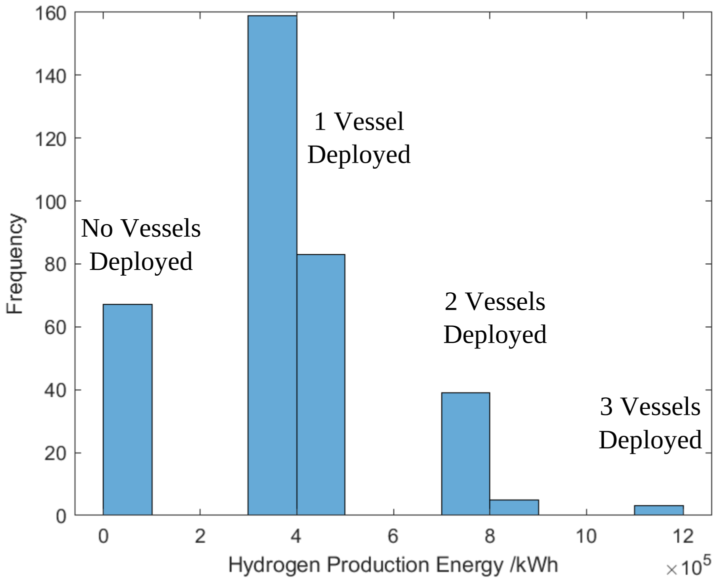


Figure 30: Histogram of Daily Hydrogen Production Energy Required to Meet the Demands of O&M Vessels for the Humber Gateway Wind Farm

5.2.2.2 Fuel Volume

It is important to consider hydrogen demand per vessel outing to understand how much hydrogen fuel a vessel would be expected to carry. To achieve this the hydrogen model was applied to the fuel consumption measured on days that only a single vessel was deployed. The results are displayed in Figure 31 showing that on average a Humber Gateway O&M vessel would require 7192 kg of Hydrogen to complete its journey on a single shift, with a maximum variation of +/- 600 kg. While mass remains consistent, the equivalent volume of fuel depends on the state hydrogen is stored in. Therefore, the hydrogen demand, by mass, per vessel outing (Figure 31) was converted to a volumetric demand with the results given in Table 13.

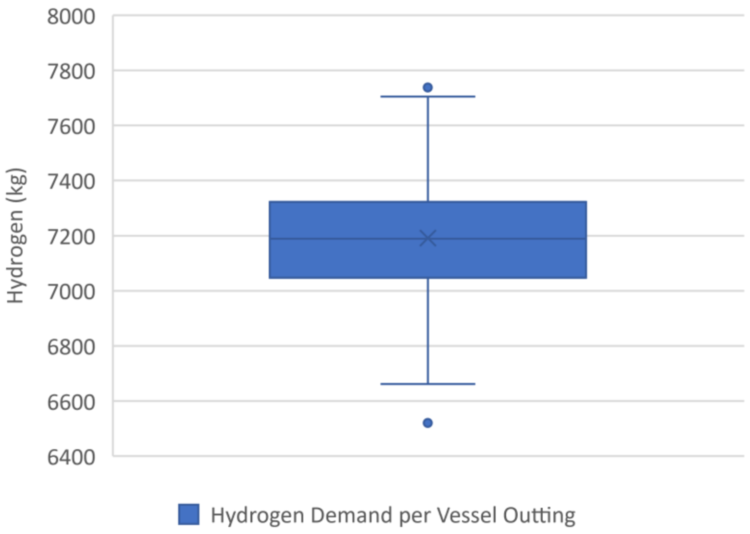


Figure 31: Variation in hydrogen fuel demand per vessel outing calculated for the Humber Gateway Wind farm

In Table 13, the term fuelling volume is defined as the volume of fuel required to complete a voyage, thus indicating required fuel tank capacity. The results show that the volume of hydrogen required is significantly higher than when MGO was used. This is the expected result, and one of the key challenges of implementing alternative fuels as discussed in section 1.1.1, which provides further confidence in the hydrogen model methodology applied in this study. Additionally, key technical implications can be concluded from a comparison of the results for liquid and gaseous hydrogen, as discussed below.

Table 13: Humber Gateway O&M Vessel Fuel Requirements per voyage, predicted by MO-VUMA (Simulation 2).

Fuel Type	Max Fuelling Volume (L/outing)	Average Fuelling Volume (L/outing)
Hydrogen (Gas, 500 bar)	235,333	217,939
Hydrogen (Liquid, -253C)	11,094	10,274
MGO	1,880	1,741

5.2.2.2.1 Fuelling with Hydrogen Gas

The results show that 235,333 L hydrogen gas, equating to a 235 m^3 fuel tank, would be required to fuel a single maintenance vessel outing for the Humber Gateway windfarm. Currently the average CTV is 24 m in length, with a fuel tank capacity between 2000-4000 L. As such it is concluded that accommodating this high volume on a CTV is unattainable. The implications for the feasibility of using compressed hydrogen to fuel the Humber Gateway O&M vessels are that there would need to be significant change to vessel range, with increased refuelling rates. At present it is assumed a vessel can service 3-4 turbines per outing therefore there is limited lee way for reduction of this without requiring significantly more vessels to meet the O&M demands

5.2.2.2.1 Fuelling with Liquid Hydrogen

The modelling results indicate that, in order to maintain the current vessel operational characteristics, a maximum of 11,094 L / 11 m^3 of liquid hydrogen would need to be carried by a vessel to fuel a single maintenance journey. Windcat Workboats have demonstrated a lengthened CTV to accommodate additional 6000L hydrogen fuel tank alongside a diesel tank [72]. This indicates there is scope to accommodate the necessary volume of liquid hydrogen with only small changes to vessel range and operational strategy. Additionally, this study has highlighted vessel loitering in field as the highest proportion of fuel usage during a maintenance outing. Subsequently, a combined offshore hydrogen production, vessel docking and refuelling station may further alleviate fuel tank size limitations.

6.0 Conclusion

This study has introduced a new tool, MO-VUMA, for the simulation of O&M vessel movements around a wind farm to assess fuel consumption. Results from the simulation of the Humber Gateway Windfarm using the MO-VUMA tool estimated that annually 589,262 L of MGO is used by O&M vessels, contributing to 1831 ktCO2e emissions. For these vessels to be powered by hydrogen as an alternative fuel, the annual demand was calculated to be 2428151 kg H_2. Modelling of PEM based wind powered hydrogen production system showed that 131-145 GWh would be required to meet this demand, depending on if hydrogen is supplied in a gaseous or liquid state. This represents 16-18% of the Humber Gateway's annual energy output, thus the analysis illustrated the feasibility of fuelling O&M vessel with on-site hydrogen production. This result also falls within the average curtailment levels of wind farms in the UK. Therefore, the findings from this study introduces the possibility for operators to alleviate curtailment issues while producing their own fuel to power the sites service vessels.

Evaluation and validation of the MO-VUMA tool yielded results for O&M vessel fuel consumption that challenged current values, with a 209% higher estimate than that reported from the ORE COMPASS tool. However, through the comparative study it was concluded that the time-domain and statistical basis of the MO-VUMA tool advances current modelling, in particular by better representing turbine to turbine movement. As such the MO-VUMA methodology provides an improved means of estimating vessel usage, fuel consumption and emissions. Additionally, prior research has shown that offshore wind LCAs have previously fallen short of identify the true magnitude O&M vessel emissions due to high level assumptions producing underestimates of fuel usage. As such the MO-VUMA tool could have additional value strengthening research in this area.

7.0 Future Work

The analysis of the Humber Gateway case study illustrated that the model and methodology presented in this study can be used to assess hydrogen demand for fuelling O&M activities as specific wind farm sites. The methodology could further be applied to evaluate other alternative fuels and make comparisons base on production energies required as well as vessel tank volume, or range limitations. Additionally, the current research could be extended by using the presented models to evaluate trends based on number of turbines and distance from port.

Finally, one of the current limitations of the MO-VUMA model is that it does not factor in seasonal variation. An improvement could be made by expanding the model to account for weather effects on vessel deployment and turbine failure. This would allow the study of daily hydrogen production and demand variation, which will influence understanding of hydrogen storage requirements for O&M vessel fuelling. This could form a valuable future research project.

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Appendix

Below is an example code snipped from the modelling of scenario 2 for this project. The author would like to note that the model was built with no prior experience of MATLAB or programming. As such, many improvements can be made to the efficiency of the scrip.

Inputs

```
%Wind Farm Layout
TurbineCols = [9 3]; %[quantity, spacing(km)]
TurbineRows = [8 3.5];
    length = (TurbineCols(1)-1)*TurbineCols(2)
    width = (TurbineRows(1)-1)*TurbineRows(2)
origin = [0 0];
distanceFromPort = 8; %km
visitRate = 0.052; %1
siteCapacity = 219; %MW
capacityFactor = 42.9; %
annualEnergyProduction = 803000; %MWh
TimeSteps = 356;

%vessel specifications
loiteringFuelConsumptionRate = 120; % L/h
transitingFuelConsumprionRate = 320; % L/h
transitSpeed = 48.152; % km/h
%-------
%emission factors
%co2eMFO = 3.107/1000;
%co2eMGO = 2.775/1000;
```

Stage 1: Model Wind Farm

```
%Create coordinate grid
[x,y] =
meshgrid(linspace(origin(1),length,TurbineCols(1)),linspace(origin(2),width,Tu
rbineRows(1)));


%Determine number of turbines and index
NoOfTurbines = TurbineRows(1)*TurbineCols(1)
turbineIdx = (1:NoOfTurbines)';


%Assign turbines to each x,y node
xy = [x(turbineIdx) y(turbineIdx)]


%Visulise Turbine Array
scatter(x,y,'filled','b')
grid on
grid minor
xlabel('x Distance (km)')
ylabel('y Distance (km)')
```

```
for ii = 1:numel(x)
    text(x(ii),y(ii)," T" + string(turbineIdx(ii)),'FontSize',8)
end
```

Stage 2: O&M Simulation and Distance Calculation

```
%Turbine Failure Model


% Generate Time Series Randomised State Array where:
% cols correspond to each turbine
% rows correspond to each Time Step (e.g Day 1, Day 2 etc)
% 0 - Active, 1 - Failed
state = rand(TimeSteps,NoOfTurbines) < visitRate
failuresPerTurbine = sum(state)
failuresPerDay = sum(state,2)'

% O&M vessel movement Model


%set starting reference / outputs
distanceTraveled=0;
totalDistanceTraveled=0;
Day = 0;
NumberFailed = 0;
numberVisited = 0;
outings = 0;
timeTranisting = 0;
cumulativeTimeTransiting =0;
timeSpentLoitering =0;
cumulativeTimeLoitering =0;
fuelconsumption_V = 0;
lhydrogenDemand_V = 0;
ghydrogenDemand_V =0;
massofH2 = 0;
energyrequired = 0;
summaryTable =
table(Day,NumberFailed,numberVisited,outings,distanceTraveled,totalDistanceTra
veled,timeTranisting,cumulativeTimeTransiting,timeSpentLoitering,cumulativeTim
eLoitering,fuelconsumption_V,lhydrogenDemand_V,ghydrogenDemand_V,massofH2,ener
gyrequired);


for day=1:1:TimeSteps
    Day = day;
    NumberFailed = nnz(state(day,:));
    %Initialize current position etc
    currentPosition = origin;
    numberVisited = 0;
    completedVisits = 0;
    outings = 0;
    distanceTraveled = 0;
    timeTranisting = 0;
```

```
    timeSpentLoitering =0;
    fuelconsumption_V = 0;
    fuelconsumption_M = 0;
    hydrogenDemand_M = 0;
    if NumberFailed==0;
        %do nothing
    elseif NumberFailed<=2
    % less than 3 failed turbines so no outing. roll over failed to next day.
        state = rollOverFailedv2(state,day);
    elseif NumberFailed>2  %0
    %If there are more than 2 failed turbines deploy vessel and account for
port-site travel
        distanceTraveled = distanceFromPort*2;
        outings = 1;
    end
% Calculate and add up vessel movement around failed turbine turbines
    while any(state(day,:))
        %find failed turbines
        InxOfFailed = find(state(day,:));
        positionsOfFailed = xy(InxOfFailed,:);
        % select and move to closest (nearest neighbour) failed turbine
        [nndistance,nnidx] =
nearestNeighbour(positionsOfFailed,currentPosition);
        distanceTraveled = distanceTraveled + nndistance;
        % update selected turbine state to active
        state(day,InxOfFailed(nnidx)) = 0;
        % update current position to selected turbine
        currentPosition = xy(InxOfFailed(nnidx),:);
        completedVisits = completedVisits+1;
        numberVisited = numberVisited+1;
        %once vessel has visited 4 turbines return to origin
        if completedVisits == 4
            % add distance back to orgin
            [distoOrigin] = nearestNeighbour(origin,currentPosition);
            distanceTraveled = distanceTraveled +distoOrigin;
            %update position
            currentPosition = origin;
            %reset visit count
            completedVisits = 0;
            % 2 or more still failed deploy another vessel
            if nnz(state(day,:))>2
                outings = outings+1;
                %add pot-site travel
                distanceTraveled = distanceTraveled + distanceFromPort*2;
            % less than less than 2 still failed, roll over failed to next
day.
            elseif nnz(state(day,:))<=2 && nnz(state(day,:))~=0
                state = rollOverFailedv2(state,day);
            else
                % do nothing
            end
```

```
        end
    end
    if completedVisits>0 && completedVisits<4
        % add distance back to orgin
        [distoOrigin] = nearestNeighbour(origin,currentPosition);
        distanceTraveled = distanceTraveled +distoOrigin;
    end
    totalDistanceTraveled = totalDistanceTraveled + distanceTraveled;


    timeTranisting = distanceTraveled/transitSpeed;
    cumulativeTimeTransiting = cumulativeTimeTransiting + timeTranisting;


    timeSpentLoitering = (12*outings) - timeTranisting;
    cumulativeTimeLoitering  = cumulativeTimeLoitering +timeSpentLoitering;


    fuelconsumption_V = 
(timeSpentLoitering*loiteringFuelConsumptionRate)+(timeTranisting*transitingFu
elConsumprionRate);

    [lhydrogenDemand_V,ghydrogenDemand_V,massofH2] = 
hydrogenDemand(fuelconsumption_V);
    energyrequired = energydemand(massofH2);

%Record calculated data into summary Table
    summaryTable(day,:) = 
{Day,NumberFailed,numberVisited,outings,distanceTraveled,totalDistanceTraveled
,timeTranisting,cumulativeTimeTransiting,timeSpentLoitering,cumulativeTimeLoit
ering,fuelconsumption_V,lhydrogenDemand_V,ghydrogenDemand_V,massofH2,energyreq
uired};
end
```

```
function [distance,idx] = nearestNeighbour(candidates,startingPosition)
        %calculate distance of each from current position
         % [(x2-x1)^2 (y2-y1)^2]
         i = (candidates - startingPosition).^2;
         % sqrt[i(x) + i(y)]
        distances = sqrt(i(:,1) + i(:,2));
        %[distance, idx] = min(distances);
        [distance, idx] = min(flip(distances));
end




function newStateArray = rollOverFailedv2(stateArray,day)
        if day==size(stateArray,1)
            % do nothing
        else
```

```
        InxOfFailed = find(stateArray(day,:));
        %move failed state to next day that isnt already marked as failed
        for turbine = InxOfFailed
        nextday = day+1;
            while stateArray(nextday,turbine)~=0
                nextday=nextday+1;
                if nextday>=size(stateArray,1)
                    stateArray(nextday,turbine) = 0;
                end
            end
        stateArray(nextday,turbine) = 1;
        stateArray(day,turbine) = 0;
        end
        end
        newStateArray = stateArray;
end


function [volumeoflH2,volumeofgH2,massofH2] = hydrogenDemand(fuelConsumtion)
%Marine Fuel
mGoEnergyDensity = 38; %MJ/L
%liquid Hydrogen
lH2Density = 0.07; %kg/L m^3 (Hydrogen production from offshore wind parks:
Current situation and future perspectives)
h2LHV = 8.28; %MJ/kg
%compressed gas hydrogen 500 bar
gH2Density = 0.033; %kg/L
% Engine effcicy
ceEfficiency = 0.45;
fcEfficiency = 0.50;  %% ref


        energyrequiredfromMarineFuel = fuelConsumtion * mGoEnergyDensity *
ceEfficiency;
        EnergyrequiredfromHydrogen = energyrequiredfromMarineFuel /
fcEfficiency;
        massofH2 = EnergyrequiredfromHydrogen / h2LHV;
        volumeoflH2 = massofH2 / lH2Density;
        volumeofgH2 = massofH2 / gH2Density;


end


function [energyrequiredg] = energydemand(massofH2)
   H2EnergyConsumption = 54; %kWh/kg
   energyrequiredg = massofH2*H2EnergyConsumption;
end
```

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