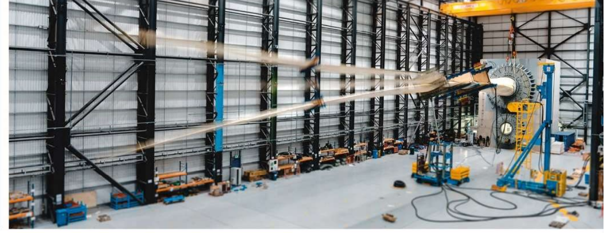

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SETTING A BENCHMARK FOR DECARBONISING O&M VESSELS OF OFFSHORE WIND FARMS

EXECUTIVE SUMMARY

As a growing number of nations set ‘Net Zero’ emissions targets in order to tackle the effects of climate change, increasing focus is being placed on decarbonising industry. With the huge growth expected in offshore wind, a sector which will contribute significantly to these ‘Net Zero’ goals, an area that is becoming of interest is the decarbonisation of vessels involved in the 20+ year operations and maintenance (O&M) phase of offshore wind farms.

This study aims to provide an estimate of annual vessel usage during the O&M phase of modern and future offshore wind farms and therefore define a benchmark for the associated fuel emissions. It is not intended to be a comprehensive Lifecycle Assessment (LCA) as it does not account for embodied carbon, however, the final result may feed into future LCA calculations. Two reference offshore wind farms of different sizes and distances to shore are analysed to investigate emissions produced by Crew Transfer Vessels (CTVs) and Service Operation Vessels (SOVs).

In scenario 1, the CTVs used for O&M of a small offshore wind farm were found to produce 3.6 tonnes of carbon dioxide equivalent (CO_2e) per Gigawatt hour (GWh) of energy generated by the wind farm per year. The annual usage of CTVs for the farm was calculated to be 4,295 hours.

Scenario 2 showed lower emissions by this metric. The SOV used for O&M of a larger offshore wind farm further from shore was found to have an annual usage of 6,305 hours and produce 2.1 tonnes of CO_2e per GWh per year. Suggested further work includes analysing the ‘mothership’ concept, whereby an SOV is joined in-field by CTVs acting as ‘daughter craft’.

INTRODUCTION

Why focus on decarbonisation?

Offshore wind is expected to be a major contributor to the clean energy mix of global economies, as many countries target 'Net Zero' emissions.[i] For example, the UK government has a target to reach 40GW of installed offshore wind capacity by 2030, as part of an effort to achieve Net Zero by 2050.[ii] It is clear that offshore wind power is much less carbon-intensive than other forms of electricity generation (Figure 1).[iii]

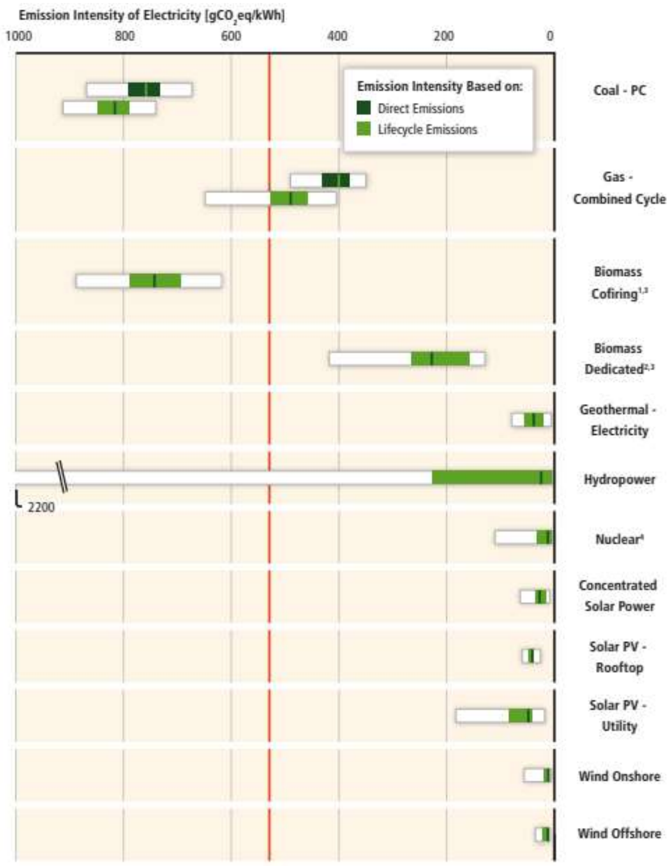

Figure 1: Emissions intensity of existing forms of electricity (Source: Bruckner et al. 2014)

However, the processes of developing, constructing, operating, and maintaining an offshore wind farm each incur a carbon footprint from embodied carbon of materials and equipment, as well as live emissions produced by vessels. This needs to be minimised to speed up the process of reaching Net Zero targets.

The cost of offshore wind has dropped dramatically in the past few years. For example, the third UK auction round (2019) for offshore wind farms produced the lowest strike prices of £39.65/MWh (2012 prices), which is comparable to the wholesale cost of electricity.[iv] In other words, offshore wind is on the verge of being a subsidy-free industry. As a result, other metrics and Key Performance Indicators

(KPIs) are expected to start playing a larger part in defining offshore wind farms' performance. One of these new KPIs is likely to be the carbon footprint, as the 'race to Net Zero' comes to the fore.

What does this report aim to do?

This report aims to provide an estimate of annual vessel usage during the Operations and Maintenance (O&M) phase of existing and future offshore wind farms and therefore define a benchmark for the associated fuel emissions. This information can feed into efforts to decarbonise the O&M phase of offshore wind farms and contribute to the International Maritime Organization's (IMO) strategy of reducing the annual Greenhouse Gas (GHG) emissions of shipping by at least 50% by 2050, compared to 2008.[v]

Why ORE Catapult?

ORE Catapult acts as an independent, centralised, forward-thinking organisation at the heart of the offshore renewable energy industry, working closely with partners across industry and academia to develop new ways of working and prove, de-risk and develop promising new technologies. This publicly available report has been compiled by ORE Catapult using in-house modelling expertise and gathering knowledge from a wide range of industry and academic sources.

LITERATURE REVIEW

Several studies have looked at identifying the size of the carbon footprint for offshore wind farms by undertaking Lifecycle Assessments (LCAs). LCAs take a holistic view of the offshore wind farm, including embodied carbon of all materials used on the project. As a result, the vessel emissions incurred during the O&M phase are usually estimated at a high level in these studies.

For example, Huang et al. in 2017 assumed that offshore wind turbines typically undergo one to two instances of scheduled (i.e. planned or preventive) maintenance per year and unscheduled (i.e. unplanned or corrective) maintenance one to four times per year.[vi] Another example is Reimers et al., who estimated in 2014 that an offshore wind farm would require 120 annual person-hours for planned maintenance and that there would be 6.27 wind turbine failures per year requiring unplanned maintenance.[vii] Operations and maintenance of offshore wind farms is complex with many variables and constraints. Therefore, high-level assumptions such as these might result in unrealistic estimates of vessel usage. Arvesen et al. extracted more detailed O&M vessel usage information from various sources for a 2013 paper but conceded that the limited data sources likely resulted in optimistic turbine reliability assumptions.[viii]

The global deployment of offshore wind farms has increased significantly in recent years, which has allowed for more accurate estimates of turbine reliability and, as a consequence, better forecasts for vessel usage due to unplanned maintenance. A 2016 paper by Carroll et al. presents a detailed breakdown of failure rate estimates by subassembly (e.g. gearbox, blades etc.) and by cost category (e.g. major replacement, minor repair etc.).[ix] In addition, industrial databases such as the System Performance, Availability and Reliability Trend Analysis benchmarking system (SPARTA) have become vital for compiling reliability data and therefore refining estimates of O&M vessel usage.[x]

METHODOLOGY

The methodology for this paper involves using ORE Catapult's internal O&M simulation tool, COMPASS (Combined Operations and Maintenance, People, Assets and Systems Simulation), applying high-level adjustments, and combining the resulting estimates of vessel usage with emissions metrics provided by the UK Government's Department for Business, Energy & Industrial Strategy (BEIS). Two reference offshore wind farms are used for the analysis.

ORE Catapult's COMPASS Tool

The COMPASS model, developed by engineers at ORE Catapult, is a Python-based O&M simulation tool (see ORE Catapult 2020 for an overview of O&M simulation tools) that is interfaced with Microsoft Excel for the input and output files.[xi] It is intended primarily for obtaining reliable estimates of Operational Expenditure (OPEX) of offshore wind farms to inform internal cost modelling projects. It takes characteristics of an offshore wind farm, such as number of turbines, site capacity etc., and applies a series of O&M activities. Activities are O&M tasks that occur on the wind farm assets (e.g. turbines, cables etc.) and provide a detailed bottom-up modelling methodology, down to subsystem level. For example, a transition piece will undergo scheduled external inspections. A full list of the subsystems considered in this modelling is provided in the appendices (Table 5). In addition, some subsystems are assigned secondary level subsystems; for example, a blade adjustment system (i.e. the subsystem) contains a pitch actuator (i.e. the secondary level subsystem).

Each O&M activity can either be planned (i.e. scheduled) or unplanned (i.e. corrective) and has been assigned a rate (i.e. times per year for scheduled maintenance, or failures per year for corrective maintenance). These rates have been defined from a combination of publicly available sources (particularly Carroll et al. and the SPARTA Portfolio Review 2016) and the experience of the team at ORE Catapult.[ix, xii] Activities are also assigned an average duration and logistical requirements in the form of people and vessels needed. Figure 12 in the appendices shows the estimated annual durations (i.e. annual rate multiplied by average duration) of all activities in each subsystem (and secondary level subsystems).

The 'deterministic' mode of the COMPASS tool operates by collating this rate and duration information and results in an estimation of each vessel's annual usage. The results can be presented at the lowest level (i.e. per activity and per subsystem for each asset and logistic type) or can be 'rolled' up into a high-level summary. This methodology does not take weather downtime into account, nor does it allow for more complex modelling of operations such as optimising vessel usage in any given day. The COMPASS tool also has a 'time-domain' mode that aims to address these issues; however, it is yet to be validated and has, therefore, not been used for this study.

The COMPASS tool's outputs identify the amount of time each vessel may spend 'loitering' at site (i.e. in-field with the engine idling). The analysis in this report also considers vessel transit time. In the case of a Crew Transfer Vessel (CTV, see example in Figure 2), this would be a transit from the port to a turbine and back again, as well as any time spent transiting between turbines. In the case of a Service Operation Vessel (SOV, see example in Figure 3), this would be a transit from its offshore station at the site to a turbine (or between turbines), as well as a fortnightly transit back to port for resupply (and back to the offshore station again). This SOV return-to-port frequency is the lower limit in a Guide to an Offshore Wind Farm (with the maximum stated as every four weeks).[xiii]

In this study, we have used the number of transfers stated in the SPARTA portfolio review for 2018/19 (i.e. 6.81 personnel transfers per turbine per month) to inform the number of transits undertaken by these vessels.[xiv] For clarity, this means that each turbine is visited an average of 6.81 times per month by different technicians. For example, a team of two technicians transferring from a vessel onto a turbine would count as two personnel transfers. We have assumed that the team accessing each turbine for any remedial works is made up of an average of 2.5 people, meaning that each turbine is visited by a vessel approximately 2.7 times per month on average.

Figure 2: CTV Typhoon Tow (Source: CWind)

Figure 3: SOV Windea Jules Verne (Source: GE)

Scenario Selection

Windfarm service vessels, mainly CTVs and SOVs, are built to serve offshore wind farms in construction and O&M phases. CTVs are designed to carry personnel and cargo (e.g. tools and small spare parts) from a port to the wind farm and use a 'push on' method to allow technicians to transfer onto turbines. CTVs can transport a maximum of twelve or twenty-four personnel (depending on vessel size) at any one time. CTVs are typically used for near-shore wind farms. More modern wind farms are being built further from shore, in part to access higher wind speeds, where the use of CTVs can become unfeasible due to the limited working time of personnel. SOVs can be more attractive in these situations, despite the significantly higher cost, as they can carry many more technicians (e.g. 50-200, depending on size) and provide a stable 'walk-to-work' platform for turbine access, therefore increasing wind farm availability and revenue.

Two distinct types of offshore wind farms have been considered in this analysis. The first has an O&M strategy centred on CTVs transporting technicians between the port and different turbines. It uses 3.6MW turbines, representative of some offshore wind projects currently in operation in the UK today. The second scenario is a larger wind farm located further from shore, which utilises one (or more) SOV. It has 12MW turbines and is intended to be representative of projects due to be deployed in the UK from 2025-2030. Both of these scenarios are assumed to have monopile foundations. Table 1 summarises the key parameters of the two scenarios.

Table 1: Key parameters of the two offshore wind farm scenarios modelled

Parameter	Units	Scenario 1	Scenario 2
Primary O&M Vessel Type	text	CTV	SOV
Turbine Size	MW	3.6	12
Turbine Numbers	#	50	100
Site Capacity	MW	180	1,200
Distance from Port	km	20	130

To obtain the necessary input data for the COMPASS tool defining the O&M activities in scenario 1, engineers at ORE Catapult have leveraged internal staff members with experience of operating similar-sized offshore wind farms. The assumption is that the O&M strategy for the scenario 1 wind farm would be a mixture of 'traditional' (e.g. rope access technicians, divers etc.) and more 'modern' methods, most notably robotics (e.g. remotely operated vehicles, airborne drones etc.). The same O&M activities have been used for scenario 2 in this study. However, it is expected that robotics (i.e. autonomous underwater vehicles, unmanned surface vessels etc.) will be more commonplace in the O&M phase of offshore wind farms when projects such as the one defined in scenario 2 are operating. These methods can speed up O&M activities (e.g. visiting more turbines per day), thereby reducing vessel usage and the associated fuel emissions.

The intention of modelling these two scenarios is to benchmark the vessel emissions for the two distinct types of offshore wind farms and highlight that CTVs and SOVs have different operational behaviours.

It should be noted that an SOV can also utilise 'daughter craft', which are a type of CTV deployed from the 'mothership', allowing personnel to be rapidly transported around the wind farm for the more menial inspection and repair tasks. This concept has not been analysed in this study.

High-Level Adjustments

High-level adjustments are required to ensure the COMPASS tool's bottom-up modelling represents the realistic operation of vessels. As stated previously, this includes adding transit time (both port-to-site transits and turbine-to-turbine) to the 'loitering' times (i.e. in-field) identified in the modelling. Another area requiring adjustment is the optimisation of personnel transfer.

CTVs typically can transport between twelve and twenty-four technicians (depending on vessel size) to site, meaning that more than one turbine could be visited per port-to-site transit. For scenario 1 in this study, it is assumed that one port-to-site transit will see four turbines visited (i.e. ten technicians in total transited where the average team consists of 2.5 technicians). This means that the initial bottom-up estimates from the COMPASS tool for loitering in-field are divided by four. However, there is some time added due to transiting between turbines whilst onsite (assumed to average 2.5 km between turbines for the size of turbines and farm in scenario 1 – i.e. once at site, an extra 15 km is travelled to drop technicians off at all four turbines on that trip and pick them back up).

As the wind farm in scenario 2 is bigger and uses larger turbines (therefore has increased spacing between turbines), it is assumed that the scenario 2 SOVs would travel an average of 10 km between turbine transfers around the wind farm. For the SOV 'loitering' time (i.e. in-field) in scenario 2, we have assumed that the vessel will spend a maximum of one hour at a turbine before becoming available for further work. This time allows for the safe transfer of technicians using walk-to-work platforms. SOVs have a significantly larger personnel capacity than CTVs, so they are more likely to spend time transiting around the wind farm, dropping off and picking up technicians.

Vessel Specifications and Emissions Metrics

To calculate carbon emissions produced during the O&M phase of the reference offshore wind farms, the usage estimates described previously need to be combined with vessel specifications in terms of fuel type and fuel consumption and emissions metrics from BEIS.

We have assumed that the reference vessels in this study, CTVs and SOVs, use Marine Fuel Oil (MFO) and Marine Gas Oil (MGO), respectively, as the primary fuel source. It is assumed that SOVs, classed as more modern than CTVs, use MGO due to the lower sulphur content. It should be noted that despite our assumptions for this study, some CTVs are capable of also using MGO following appropriate adjustments. The fuel consumption of SOVs when loitering in-field is deemed to be lower than that of CTVs as they often have hybrid electric power systems (e.g. Windea Jules Verne).[xv] However, during transit, fuel consumption is likely to be considerably larger for an SOV than a CTV due to the significantly larger tonnage. Our assumptions for vessel specifications are shown in Table 2, alongside relevant data sources. Where the DTOceanPlus vessels database has been used, it is assumed that an SOV has similar properties to an Anchor Handler Tug Supply vessel (AHTS) in terms of fuel consumption and transit speed.[xvii]

Table 2: Assumed vessel specifications

Vessel Type	Crew Transfer Vessel (CTV)	Service Operation Vessel (SOV)
Primary Fuel	MFO	MGO[xvi]
Secondary Fuel	N/A	Battery Electric
Fuel Consumption per Hour, Transiting	320 litres/hour[xvii]	1,000 litres/hour[xvii]
Fuel Consumption per Hour, In-field/Loitering	130 litres/hour[xviii]	120 litres/hour[xvi]
Transit speed (average)	23 knots[xvii] (42.6 km/hour)	12 knots[xvii] (22.2 km/hour)

The UK Government, via BEIS, provides conversion factors that organisations can use to report greenhouse gas emissions.[xix] Table 6 and Table 7 in the Appendices highlight the BEIS conversion factors used for this analysis. Combining our assumptions for vessel specifications with the BEIS conversion factors for MFO and MGO emissions, using the following equation, produces the figures shown in Table 3 for use in the bottom-up modelling.

$$Emissions\ per\ Hour = Emissions\ per\ Litre \times Vessel\ Fuel\ Consumption\ (l/h)$$

Table 3: Emissions per hour used in this study

Parameter	Units	CTV	SOV
Fuel Type	**-**	**MFO**	**MGO**
CO_2 produced at average transit speed	kg CO_2 / hr	984.7	2,737.8
CH_4 produced at average transit speed	kg CH_4 / hr	0.4	0.7
N_2O produced at average transit speed	kg N_2O / hr	14.0	36.9
CO_2e produced at average transit speed	***kg CO_2e / hr***	***999.1***	***2,775.4***
CO_2 produced while loitering (in-field)	kg CO_2 / hr	400.0	328.5
CH_4 produced while loitering (in-field)	kg CH_4 / hr	0.2	0.1
N_2O produced while loitering (in-field)	kg N_2O / hr	5.7	4.4
CO_2e produced while loitering (in-field)	***kg CO_2e / hr***	***405.9***	***333.0***

RESULTS

Vessel Usage

Scenario 1

The results for scenario 1 indicate that CTVs are the primary vessel type involved in the O&M phase for the offshore wind farm, as expected, accounting for 3,767 out of 4,948 hours (76%) of annual onsite (i.e. without transit times) activity (Figure 4). They are mainly used to transfer technicians (and associated spare parts and consumables) onto turbines to repair faults (unplanned maintenance) and undertake planned works.

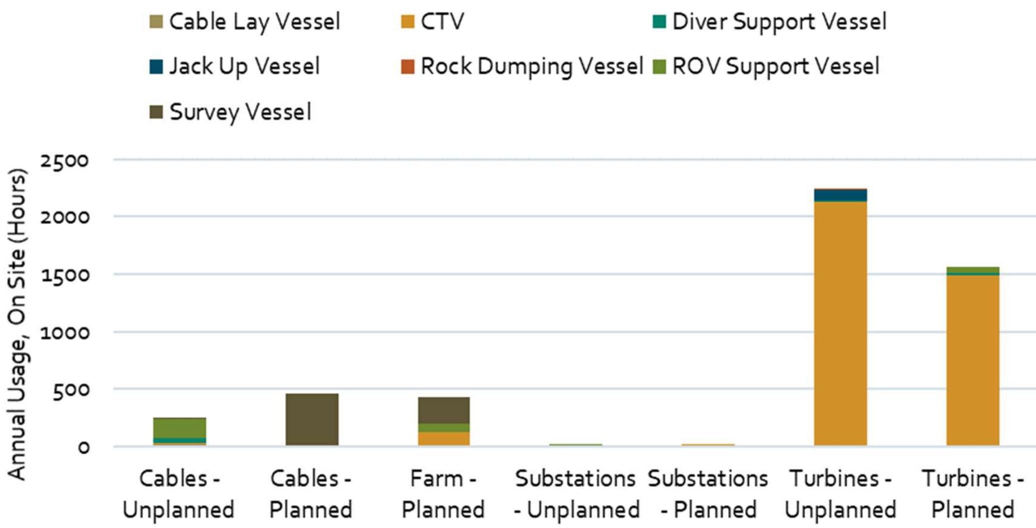

Figure 4: Vessel usage (without transit times) by asset and planned/unplanned maintenance type for scenario 1

Figure 5 shows the breakdown of CTV annual usage, including transit times between port and site, as well as turbine-to-turbine offshore transits (i.e. accounting for the personnel transfer optimisation stated previously). After dropping off all technicians to undertake turbine maintenance, it is assumed that the CTV remains offshore (i.e. in-field) in loiter mode (i.e. still consuming fuel but at a much lower rate than when transiting). From this modelling, it is estimated that CTVs are utilised for a total of 4,295 hours at the offshore wind farm per year. As planned maintenance is typically scheduled to take place in the summer months (i.e. when accessibility is high and lost revenue from downtime is minimised), the wind farm in scenario 1 would likely have one CTV on a permanent lease and another CTV on a summer-only lease.

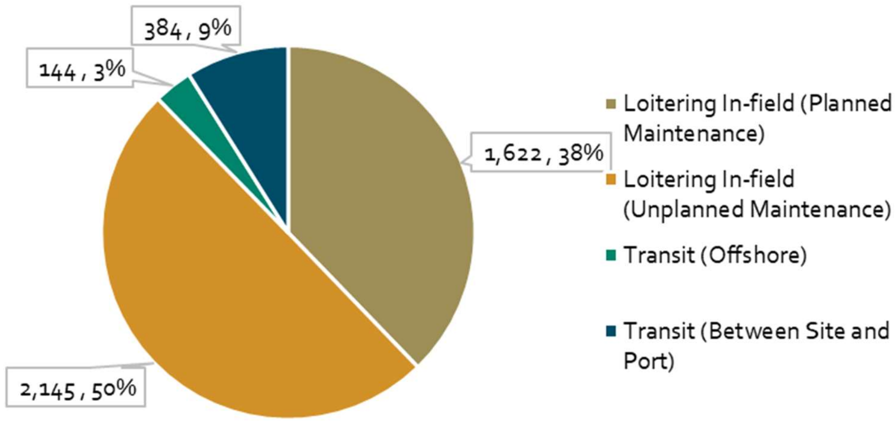

Figure 5: CTV annual usage, including transit times (all in hours) for scenario 1

Scenario 2

The vessel usage results for scenario 2 show that an SOV is the primary vessel for O&M for the larger, further from shore, offshore wind farm (Figure 6), accounting for 3,056 out of 4,339 hours (70%) of annual onsite activities (without transit times). The primary category of tasks involves transferring technicians to turbines for planned maintenance. The breakdown of annual usage for the SOV is shown in Figure 7, which includes time spent transitting both around the wind farm and the fortnightly resupply mission back to port. The modelling estimates a total of 6,305 SOV hours for the offshore wind farm in scenario 2, which equates to one SOV servicing the farm on a full-time basis.

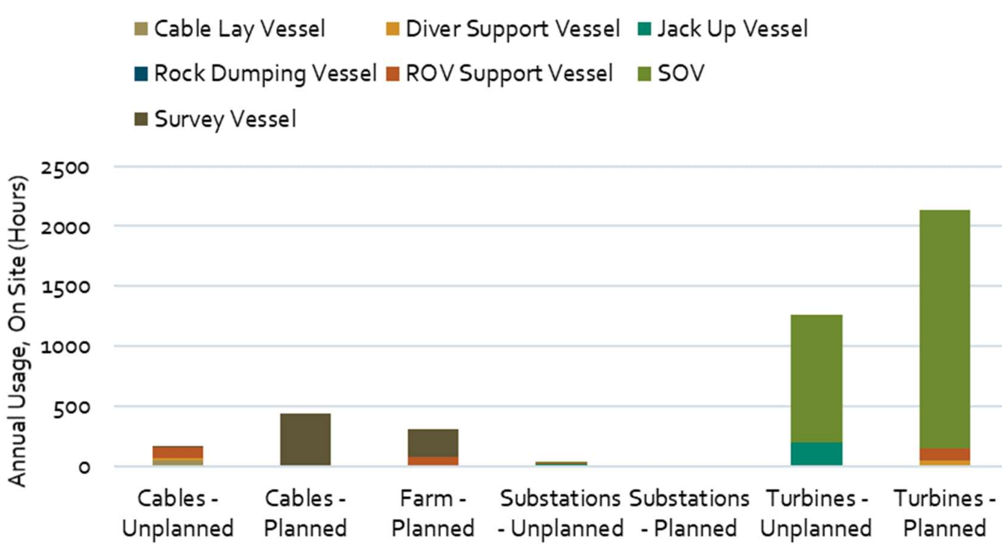

Figure 6: Vessel usage (without transit times) by asset and planned/unplanned maintenance type for scenario 2

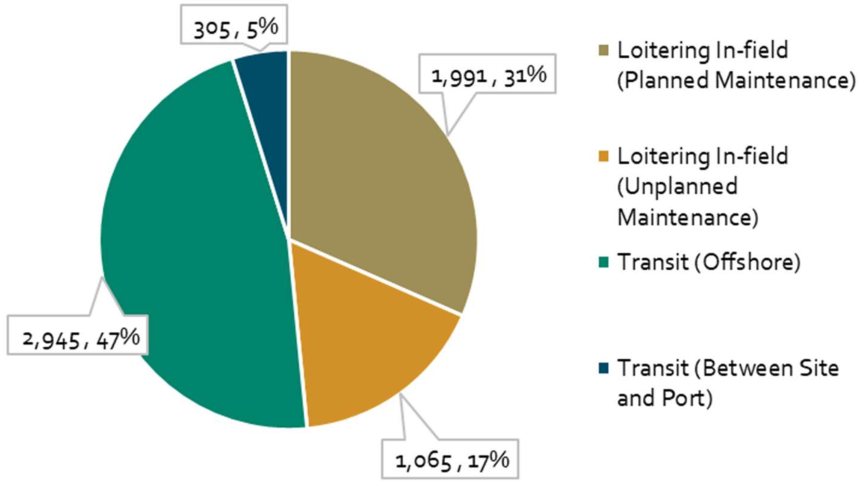

Figure 7: SOV annual usage, including transit time (all in hours) for scenario 2

Vessel Emissions

The annual usage data (i.e. hours per year) presented in the previous section can be multiplied by the relevant metric (i.e. emissions per hour) in Table 3 to calculate the annual emissions produced during the different phases of O&M in both scenarios. Figure 8 highlights the carbon dioxide equivalent produced per year by the primary vessels in each scenario (i.e. CTVs in scenario 1, SOV in scenario 2). The majority of emissions in scenario 2 stem from the SOV operating in transit mode around the offshore wind farm (i.e. 8,200 tonnes out of 10,000 tonnes).

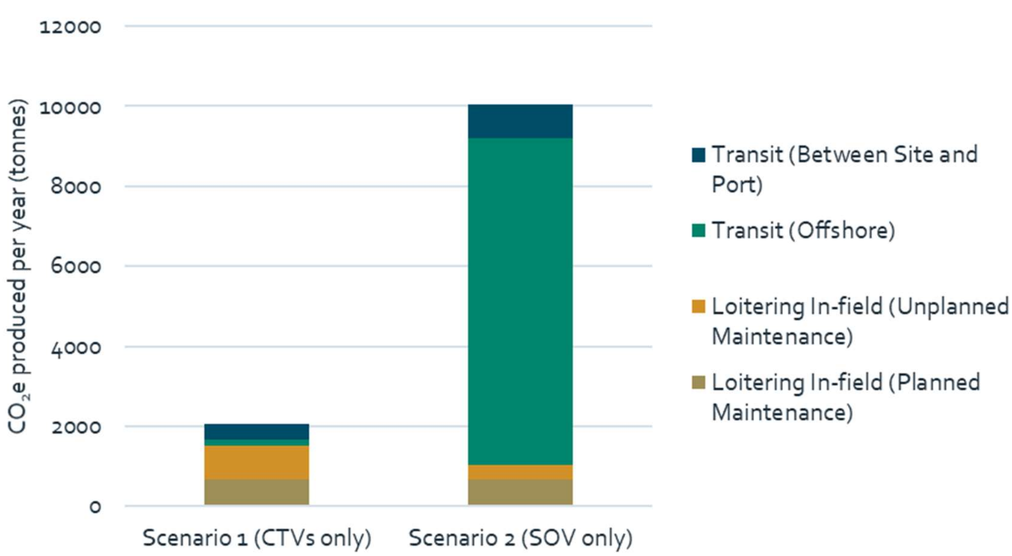

Figure 8: Primary vessel (i.e. CTV or SOV) emissions (CO_2e) caused during different phases for the two scenarios

Annual emissions can also be presented as 'per Gigawatt hour' (GWh) of energy produced. This requires an estimation of the capacity factors of the two wind farms. The wind farm in scenario 1 is representative of operational wind farms at present; therefore, the average capacity factor from the

SPARTA 2018/19 portfolio review can be used (36.05%).[xiv] Modern offshore wind farms achieve higher capacity factors, as stated by the International Energy Agency.[xx] Therefore, we have assumed a capacity factor of 45% for the offshore wind farm in scenario 2. The impact these assumptions have on expected annual energy production (AEP) is highlighted in Table 4. These estimations for AEP allow the emissions to be presented as kilotonnes (kt) per GWh of energy generated, as shown in Figure 9 for the two scenarios.

Table 4: Energy performance parameters of the two offshore wind farm scenarios modelled

Parameter	Units	Scenario 1	Scenario 2
Site Capacity	MW	180	1,200
Capacity Factor	%	36.05%	45.00%
Hours per Year	hours	8,766	
Annual Energy Production	MWh	568,826	4,733,640

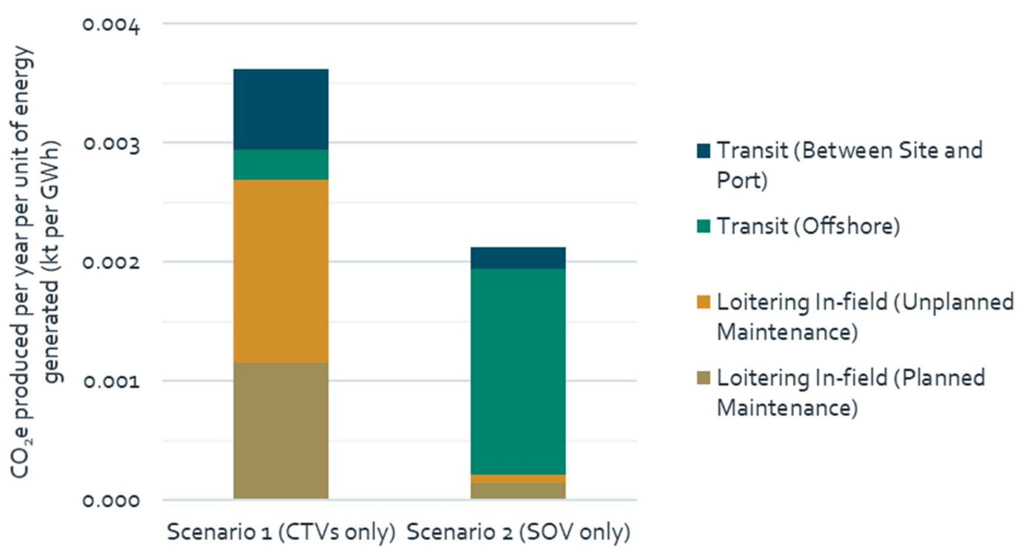

Figure 9: Primary vessel (i.e. CTV or SOV) emissions (CO_2e) per GWh caused during different phases for the two scenarios

As explained previously, high-level adjustments have been made to account for the optimisation of personnel transfer. In scenario 1, for example, it is assumed that a CTV would be able to transport the required number of technicians onto four turbines in one port-to-site transit. If this optimisation were not included (i.e. only one turbine visited every time a CTV transited to the site), then the emissions from CTVs would increase dramatically, as shown in Figure 10. It should be noted that this is an unrealistic scenario but has been included to highlight the importance of personnel transfer optimisation.

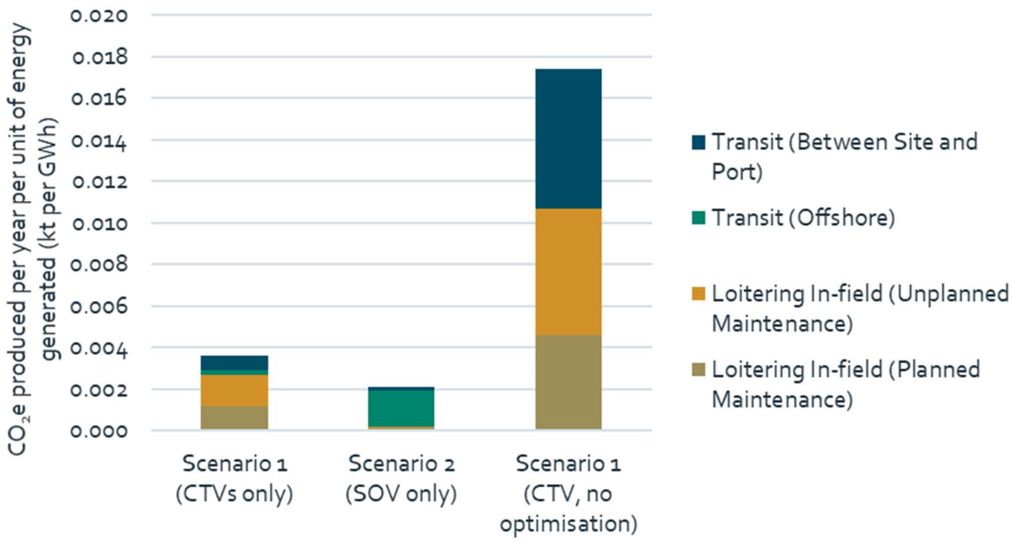

Figure 10: Primary vessel (i.e. CTV or SOV) emissions (CO2e) per GWh caused during different phases for the two scenarios, plus a non-optimised CTV case for scenario 1

The results from this modelling (i.e. 0.0036 kt/GWh of CO2e from CTVs in scenario 1 and 0.0021 kt/GWh of CO2e from SOVs in scenario 2) can be compared to other available data sources. Arvesen et al. (2013) calculated that their reference offshore wind farm's maintenance phase produced 0.00493 kt/GWh of CO_2e.[viii] In 2019, Ørsted's sustainability report stated that 42 kt of CO_2e were produced during crew transport and service vessel operations.[xxi] This figure, combined with the 12,000 GWh of energy produced by Ørsted's offshore wind farms in 2019, results in estimated vessel emissions of 0.0035 kt/GWh of CO_2e.[xxii] Ørsted's recent reporting for 2020 shows an improvement. A total of 25 kt of CO_2e produced during crew transport and service vessel operations, combined with 15,248 GWh of offshore wind generation, results in estimated vessel emissions of 0.0016 kt/GWh of CO_2e.[xxiii, xxiv] These figures are taken from Ørsted's high-level reporting available in the public domain. The improvement from 2019 to 2020 may be driven by factors such as farm performance and a concerted effort to drive down emissions. A comparison with the modelled results from this study is given in Figure 11.

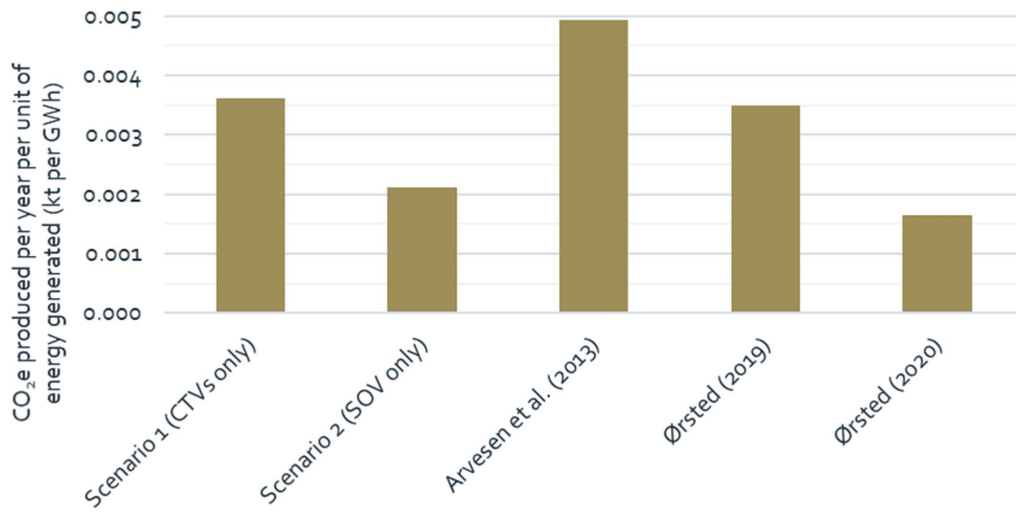

Figure 11: Vessel emissions (CO2e) per GWh for the two scenarios compared to other selected data sources

DISCUSSION

Decarbonisation technologies

Decarbonising the vessels involved in operating and maintaining offshore wind farms is important for the industry and the wider maritime sector, which is generally regarded as conservative when it comes to implementing change. Decarbonising offshore wind O&M vessels is seen as 'low hanging fruit', given the industry's clear role in achieving 'Net Zero' targets. This is then likely to feed into efforts to achieve the International Maritime Organization's (IMO) strategy of reducing the annual Greenhouse Gas (GHG) emissions of shipping by at least 50% by 2050, compared to 2008.

The modelling undertaken in this study has shown that vessel emissions during the O&M phase of offshore wind farms can vary substantially, depending primarily on the vessel strategy, size of farm, and distance from shore.

Fully decarbonising O&M vessels means running them on zero-emission fuel. In the immediate term, improvements can be made to efficiency and can therefore reduce emissions, such as the use of air lubricants or exhaust gas recirculation. Also, battery electric hybrid vessels (i.e. low emission), such as the SOV assessed in scenario 2 of this study, are a stepping-stone on the route to operating fully-electric vessels (i.e. integrating battery power). Electricity isn't the only alternative fuel being considered. Other possibilities include hydrogen, ammonia, biofuel, methanol, and solar power. Some see local availability of fuel as a barrier to using alternative fuels in the maritime sector. However, the offshore wind industry is in the unique position of generating electricity (and green hydrogen in the near future) at source (i.e. a farm could have offshore or harbour-side refuelling stations), which may mitigate this potential barrier.[xxv]

In addition to the fuel type, 'smart' O&M strategies, which reduce vessels' overall fuel consumption, can play a part in decarbonisation. For example, in this study, high-level adjustments to the initial modelling were made in both scenarios to account for the optimisation of personnel drop-off and pick-up arrangements between vessels and turbines. For scenario 1, it was highlighted that significantly higher emissions would be produced by CTVs when no personnel transfer optimisation was included. Autonomous vessels and robotics, as well as artificial intelligence-based O&M planning, are also likely to play a part in reducing the emissions produced by offshore wind farms.[xxvi, xxvii]

Modelling limitations and Further Work

Many of the caveats to the modelling methodologies used for the analysis in this study have been highlighted throughout this report. These include:

- No inclusion of more advanced O&M techniques – i.e. autonomous underwater vehicles etc.
- High-level adjustments to account for personnel transfer and associated optimisation.
- No inclusion of weather downtime – i.e. periods when a vessel is idling and waiting on suitable weather to undertake an operation.
- No inclusion of increased maintenance towards later life.
- No inclusion of the 'mothership' concept, where an SOV operates in conjunction with CTVs.
- No sensitivity analysis of fuel types.

Further work in this field should address the points made above. In particular, the high-level form of personnel transfer optimisation involved making some broad assumptions. Time-domain models would provide a better means of estimating emissions of O&M vessels, as personnel transfer strategies could be analysed in much more detail.[xi] They could also be useful for analysing the SOV 'mothership' concept, whereby CTVs are treated as 'daughter craft'. Time-domain models could also account for different O&M techniques, weather downtime, seasonal vessel leases, and time-based maintenance changes. The results of such modelling could then feed into Lifecycle Assessment (LCA) modelling to capture the total emissions (i.e. including embodied carbon and end-of-life decisions) of offshore wind farms. Every aspect of the lifecycle will need to be scrutinised if 'Net Zero' targets are to be achieved.

Identifying the fuel types that will enable the full decarbonisation of O&M vessels is an ongoing research and development area. For example, an active ORE Catapult project, funded by the Department for Transport (DfT), aims to produce a decarbonisation technology roadmap to inform industry and other stakeholders of the best route forward for the sector in terms of alternative vessel fuels.[xxviii]

KEY FINDINGS

The key results of the analysis presented in this paper include:

- Scenario 1
    - Small wind farm, 3.6MW turbines, close to shore, with a CTV-based O&M strategy.
    - CTVs are utilised for a total of 4,295 hours for the wind farm per year and produce 2,060 tonnes of carbon dioxide equivalent (CO_2e) per year.
    - CTVs produce 3.6 tonnes of CO_2e per GWh of energy generated by the wind farm per year.
- Scenario 2
    - Larger wind farm, 12MW turbines, far from shore, with an SOV-based O&M strategy
    - The SOV is utilised for 6,305 hours per year at the wind farm and produces 10,040 tonnes of CO_2e per year.
    - The SOV produces 2.1 tonnes of CO_2e per GWh of energy generated by the wind farm per year.
- The results are comparable with available data sources
    - 4.9 tonnes of CO_2e per GWh per year, estimated by Arvesen et al. (2013).[viii]
    - 3.5 tonnes of CO_2e per GWh per year derived from reported Ørsted figures for 2019.[xxi, xxii]
    - 1.6 tonnes of CO_2e per GWh per year derived from reported Ørsted figures for 2020.[xxiii, xxiv]

AUTHOR PROFILE

Dr Anthony Gray has been researching and working in the field of offshore renewable energy for seven years. He is currently a techno-economic analyst at the Offshore Renewable Energy Catapult in Glasgow, UK, where he undertakes a wide range of cost modelling activities. He gained a Masters degree in Civil Engineering (MEng) from Cardiff University in 2011 and an Engineering Doctorate (EngD) in Offshore Renewable Energy from the University of Exeter in 2017 through the Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE). His EngD research focussed on modelling operations and maintenance strategies for wave energy arrays.

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Appendices

APPENDIX A

Table 5: Subsystems of an offshore wind farm considered in the bottom-up modelling

Subsystem	Applicability	Example O&M Activity
Array Cable	Array Cable	Inspection (with Diver)
Export Cable	Export Cable	Repair (from Vessel)
Farm	Project	Environmental Monitoring (Birds)
Offshore Substation	Offshore Substation	Internal Inspection
Onshore Substation	Onshore	HV System Inspection
Monopile - Transition Piece	Turbine	Clean Boat Landing
Monopile	Turbine	External Inspection (with ROV)
Blade Adjustment System	Turbine	Blade Bearing Inspection
Central Hydraulics System	Turbine	Light Repair
Control and Protection System	Turbine	Upgrade
Drivetrain	Turbine	Gearbox Oil Replacement
Equipotential Bonding System	Turbine	Visual inspection
Generator System	Turbine	Alignment Check & Adjustment
Rotor System	Turbine	External Inspection (by Rope)
Structure and Machinery Enclosure	Turbine	Nacelle Inspection
Turbine Electrical	Turbine	Switchgear Repair
Yaw System	Turbine	Brake Light Repair
Wind Turbine	Turbine	Annual Service

APPENDIX B

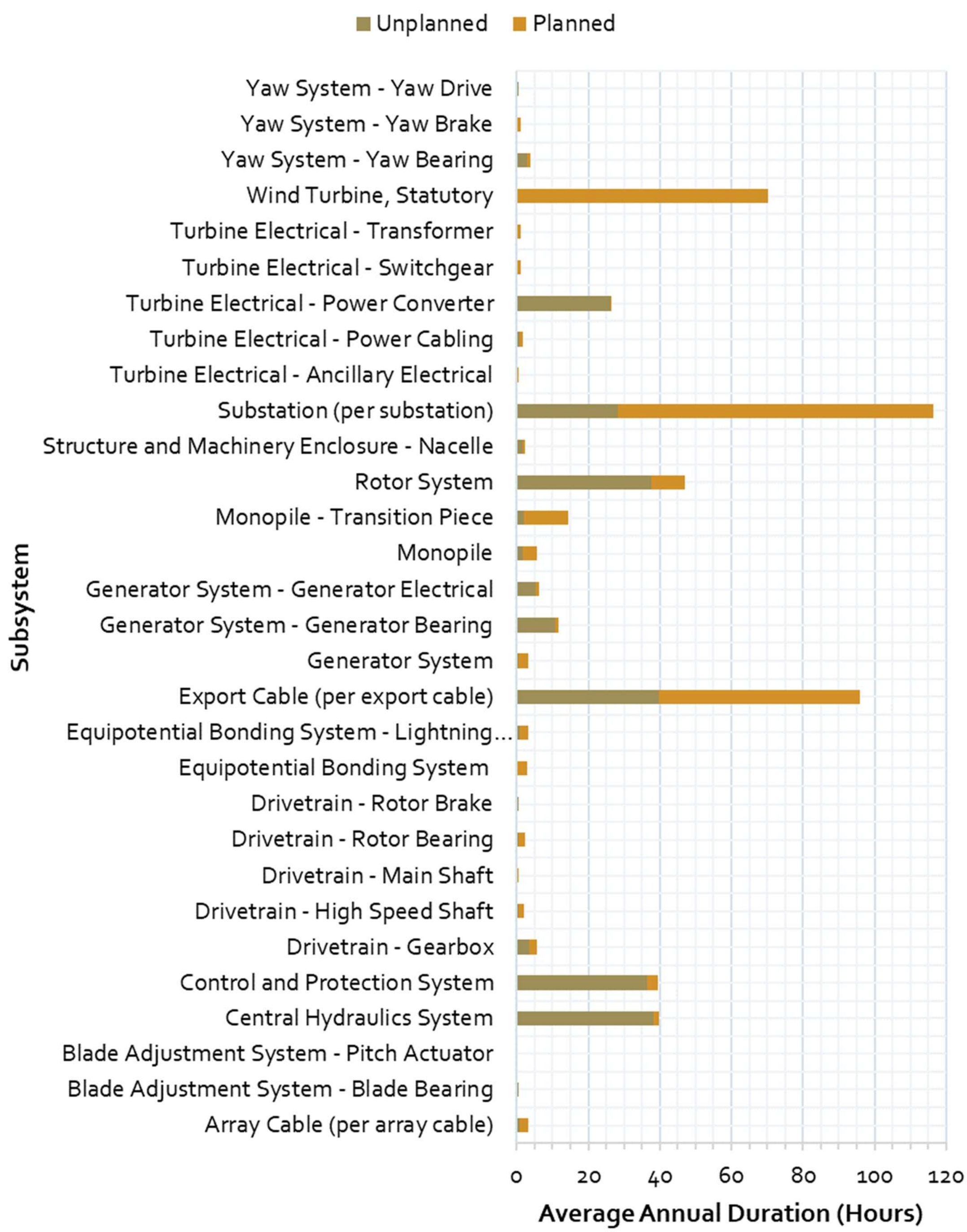

Figure 12: Assumed average annual duration of O&M activities in each subsystem (per turbine, unless stated otherwise), used for this study

APPENDIX C

Table 6: Conversion factors for emissions from Marine Fuel Oil (Source: BEIS)

MFO Emission Metric	Units	Per Tonne	Per Litre
Carbon Dioxide Equivalent	kg CO_2e	3,159.50	3.122
Carbon Dioxide	kg CO_2	3,113.99	3.077
Methane	kg CH_4	1.27	0.001
Nitrous Oxide	kg N_2O	44.24	0.044

Table 7: Conversion factors for emissions from Marine Gas Oil (Source: BEIS)

MGO Emission Metric	Units	Per Tonne	Per Litre
Carbon Dioxide Equivalent	kg CO_2e	3,249.99	2.775
Carbon Dioxide	kg CO_2	3,205.99	2.738
Methane	kg CH_4	0.81	0.001
Nitrous Oxide	kg N_2O	43.20	0.037

REFERENCES

[i] National Grid (2020). What is net zero? Available from: https://www.nationalgrid.com/stories/energy-explained/what-is-net-zero.
[ii] UK Government (2019). UK becomes first major economy to pass net zero emissions law. Available from: https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law.
[iii] Bruckner T., I.A. Bashmakov, Y. Mulugetta, H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Fungtammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H.B. Nimir, K. Riahi, N. Strachan, R. Wiser, and X. Zhang (2014). Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[iv] Noonan, M. (2020). Delivering 40GW – Accelerating the UK's Transition to Net Zero. ORE Catapult. Available from: https://ore.catapult.org.uk/blog/delivering-40gw-accelerating-the-uks-transition-to-net-zero/.
[v] International Maritime Organisation (2018). UN body adopts climate change strategy for shipping. Available from: https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx.

[vi] Huang, YF., Gan, XJ. & Chiueh, PT. (2017). Life cycle assessment and net energy analysis of offshore wind power systems. Renewable Energy. 102, pp. 98-106.
[vii] Reimers, B., Özdirik, B. & Kaltschmitt, M. (2014). Greenhouse gas emissions from electricity generated by offshore wind farms. Renewable Energy. 72, pp. 428-438.
[viii] Arvesen, A., Birkeland, C. & Hertwich, E.G. (2013). The Importance of Ships and Spare Parts in LCAs of Offshore Wind Power (and supporting information). Environmental Science & Technology. 47 (6), pp. 2948-2956.
[ix] Carroll, J., McDonald, A. & McMillan, D. (2016). Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy. 19, pp. 1107-1119.
[x] SPARTA (2020). System Performance, Availability and Reliability Trend Analysis. Available from: https://www.sparta-offshore.com/SpartaHome.
[xi] ORE Catapult (2020). What are Operations and Maintenance Simulation Tools? Available from: https://ore.catapult.org.uk/analysisinsight/what-are-operations-and-maintenance-simulation-tools/.
[xii] SPARTA (2017) SPARTA Portfolio Review 2016. Available from: https://ore.catapult.org.uk/wp-content/uploads/2018/02/SPARTAbrochure_20March-1.pdf.
[xiii] BVG Associates (2019). Guide to an offshore wind farm. Updated and extended. Available from: https://www.thecrownestate.co.uk/media/2860/guide-to-offshore-wind-farm-2019.pdf.
[xiv] SPARTA (2020) SPARTA Portfolio Review 2018/19. Available from: https://s3-eu-west-1.amazonaws.com/media.newore.catapult/app/uploads/2019/11/04144204/OREC01_8853-SPARTA-digital_FINAL.pdf?__hstc=20425319.69d600e34f7d2099a8d2d0b0e62d90eb.1552907741314.1602060305475.1602149129364.154&__hssc=20425319.1.1602160816018&__hsfp=895579783&hsCtaTracking=c9e3831f-0483-4e4b-9c8d-58d6778c793c%7C3b265be1-7aff-4221-8fd5-c964117216d8.
[xv] Ulstein (2020). Windea Jules Verne. Available from: https://ulstein.com/references/windea-jules-verne.
[xvi] Acta Marine (2019). Specification Sheet: Acta Orion, DP2 Offshore Support Vessel. Available from: https://www.actamarine.com/vessels/46/Acta-Orion.
[xvii] DTOceanPlus (2020). Vessels Database. Deliverable D5.7. Logistics and Marine Operations Tools.
[xviii] CWind (2020). Specification Sheet: CWind Endurance Swath, Crew Transfer Vessel. Available from: https://cwindprod.wpengine.com/wp-content/uploads/2017/07/CW_Endurance_Datasheet_012.pdf.
[xix] UK Government (2020). Greenhouse gas reporting: conversion factors 2020. Available from: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.
[xx] International Energy Agency (2019). Offshore Wind Outlook 2019. World Energy Outlook special report. Available from: https://www.iea.org/reports/offshore-wind-outlook-2019.
[xxi] Ørsted (2019). Sustainability Report 2019. Available from: https://orsted.com/-/media/annual2019/Sustainability-report-2019-online-version.pdf.
[xxii] Ørsted (2019). Summary 2019. Annual report and sustainability report. Available from: https://orsted.com/-/media/annual2019/AR19-EN-Summary-2019.pdf.
[xxiii] Ørsted (2020). Sustainability Report 2020. Available from: https://orstedcdn.azureedge.net/-/media/annual2020/sustainability-report-2020.ashx?la=en&rev=81afbfd3377a498ca148788a883738o5&hash=BD138224A56386F72DBDDDD24A9E44DE.
[xxiv] Ørsted (2020). Annual report 2020. Available from: https://orstedcdn.azureedge.net/-/media/annual2020/annual-report-2020.ashx?la=en&rev=3f951652f6c243ef83ded864b6b670b2&hash=94C2C2FFBA4837E0D64E8D7CB29C3B38.
[xxv] ORE Catapult (2020). Offshore Wind and Hydrogen: Solving the Integration Challenge. Available from: https://ore.catapult.org.uk/?orecatapultreports=offshore-wind-and-hydrogen-solving-the-integration-challenge.
[xxvi] ORE Catapult (2020). Autonomous motherships and robot repair teams at offshore wind farms? On their way, says MIMRee. Available from: https://ore.catapult.org.uk/press-releases/autonomous-motherships-and-robot-repair-teams-at-offshore-wind-farms-on-their-way-says-mimree/.
[xxvii] Froese, M. (2019). Improving wind-turbine O&M with artificial intelligence. WindPower Engineering. Available from: https://www.windpowerengineering.com/improving-wind-turbine-om-with-artificial-intelligence/.
[xxviii] ORE Catapult (2020). North Sea offshore wind vessels decarbonisation roadmap to be developed ahead of COP 26. Available from: https://ore.catapult.org.uk/press-releases/north-sea-offshore-wind-vessels-decarbonisation-roadmap-to-be-developed-ahead-of-cop-26/.