CORNWALL FLOW ACCELERATOR

WP5 TASK 5.1 O&M MODELLING

FINAL REPORT

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Document History

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Disclaimer

Executive Summary

The Offshore Renewable Energy (ORE) Catapult's internal Operations and Maintenance (O&M) simulation model has been configured to represent three hypothetical floating offshore wind farms off the south west coast of the UK. The purpose of this report is to highlight the expected Operational Expenditure (OPEX) and vessel emissions incurred at such a project, as well as giving an indication of port requirements.

The results of the scenario analysis estimate that a 495MW floating wind farm located at one site off the south west coast of Wales (site 1) would incur £18.7m per year in OPEX (not including some elements seen in other studies, such as seabed leasing, operational insurance and the cost of spare parts) when the O&M base is located at Pembroke Port (its nearest port). This equates to £37.7/kW annual OPEX, which is comparable to other studies analysing demonstration floating wind projects. The same site was estimated to have a time-based availability of 97.2% and an energy-based (or production-based) availability of 96.8%. However, performance of site 1 dropped (i.e. lower availability, higher OPEX) when the O&M base was located further away at Newlyn Harbour and Falmouth Harbour (both on the south coast of Cornwall). Other scenarios showed slightly different results, for example site 3 (near the Isles of Scilly) showed the lowest OPEX of the three sites, but only when the O&M base was located at either of the Cornish harbours (rather than Pembroke Port). However, site 3 also showed the lowest availability due to having the harshest weather conditions (particularly significant wave height) thereby reducing accessibility (i.e. due to operational limits of vessels). This highlights the need to consider many factors and sensitivities when judging wind farm performance and identifying the optimal O&M logistics strategy.

Vessel usage was also analysed, indicating that a Service Operation Vessel (SOV) and a survey vessel would be the most heavily utilised vessels at the site. Much of the vessels' time would be spent in port if chartered on a long-term basis, highlighting the need for permanent berth/s of suitable size at the O&M base. The largest vessels that would be required for the sites, albeit less frequently, would be floating Heavy Lift Vessels (HLVs) and Cable Lay Vessels (CLVs). An analysis of vessel emissions has indicated that an SOV would produce between 1.7kg of carbon dioxide equivalent (CO_2e) and 2.0kg CO_2e per MWh of energy produced by each 495MW site.

Further work has been suggested, particularly to refine the inputs enabling this analysis, as well as to assess different ports as the O&M base for commercial-scale floating wind projects in the Celtic Sea.

Terminology

AEP	Annual Energy Production
AHTS	Anchor Handler Tug Supply
CFA	Cornwall FLOW Accelerator
CfD	Contracts for Difference
CLV	Cable Lay Vessel
CO_2e	Carbon Dioxide Equivalent
COMPASS	Combined Operations and Maintenance, People, Assets and Systems Simulation
CTV	Crew Transfer Vessel
DP	Dynamic Positioning
ECMWF	European Centre for Medium-Range Weather Forecasts
FaBTest	Falmouth Bay Test Site
FLOW	Floating Offshore Wind
H&S	Health and Safety
HLV	Heavy Lift Vessel
Hs	Significant Wave Height
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt-hour
LEP	Local Enterprise Partnership
MGO	Marine Gas Oil
MW	Megawatt
MWh	Megawatt-hour
O&M	Operations and Maintenance
OPEX	Operational Expenditure
ORE	Offshore Renewable Energy
PPE	Personal Protective Equipment
PBA	Production-Based Availability
RD&I	Research, Development and Innovation
RDS-PP®	Reference Designation System for Power Plants
ROV	Remotely Operated Vehicle
SOV	Service Operation Vessel
SPARTA	System Performance, Availability and Reliability Trend Analysis
UK	United Kingdom

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1 Introduction

1.1 Project Overview

The Cornwall Floating Offshore Wind (FLOW) Accelerator (CFA) is being led by Celtic Sea Power (used to be known as Wave Hub Ltd) in collaboration with the University of Plymouth, University of Exeter, the Offshore Renewable Energy (ORE) Catapult and A&P Group. It is being supported by the Cornwall and Isles of Scilly Local Enterprise Partnership (LEP), Cornwall Council and Plymouth City Council. It is a collaborative partnership which aims to raise the region's profile to attract further investment and create significant export opportunities within floating wind as well as support the growth of a strong supply chain, capable of delivering low carbon footprint operations within the floating offshore wind sector. The project will act as a platform for collaboration between industry and academia, delivering knowledge transfer between universities and businesses. The project partners will undertake research, development and innovation with a particular focus on optimisation tools that will allow the virtual testing of multiple offshore operations to reduce the costs of low carbon energy production and deliver sustainable operational methodologies for offshore floating wind technologies.

1.2 ORE Catapult

ORE Catapult is the UK's flagship technology innovation and research centre for advancing wind, wave and tidal energy.[1] ORE Catapult works closely with partners from across industry and academia and uses world-leading test and demonstration facilities to develop new ways of working and prove, de-risk and develop promising new technologies. This helps to reduce the cost of offshore renewable energy, supporting business growth and delivering UK economic benefit.

1.3 Purpose of Report

ORE Catapult's internal Operations and Maintenance (O&M) simulation model, called the Combined Operations and Maintenance, People, Assets and Systems Simulation (COMPASS) tool, has been used for this report. The model has been configured to represent three hypothetical floating offshore wind farms off the south west coast of the UK, with the O&M base in each case located at one of three ports. Each farm consists of thirty-three 15MW turbines, giving a site capacity of 495MW, representative of commercial-scale projects to be deployed around the year 2030. The purpose of the report is to highlight the expected Operational Expenditure (OPEX) and vessel emissions incurred at such projects, as well as giving an indication of port requirements.

1.4 COMPASS

The COMPASS tool is a Python-based model which utilises Microsoft Excel for the input and output interface. It was originally designed for analysing traditional bottom-fixed offshore wind farms but has since been adapted to also model floating wind projects, as well as wave and tidal-stream farms. The COMPASS model is intended primarily for obtaining reliable estimates of OPEX of offshore renewable

[1] ORE Catapult website: https://ore.catapult.org.uk/.

energy farms for informing internal cost modelling projects. It takes key characteristics of an offshore wind farm, such as number of turbines, turbine coordinates, site capacity etc., and applies a series of O&M activities. These O&M activities represent tasks undertaken on all components of an offshore wind farm, including turbine sub-component level (e.g. yaw drive), and the process aims to follow the Reference Designation System for Power Plants (RDS-PP)® methodology.[2] Each maintenance activity can either be planned (i.e. recurring scheduled measures which are organised in advance) or unplanned (i.e. the result of a turbine alarm or component failure) and has been assigned a rate (i.e. interventions per year per turbine for planned maintenance, or failures per year per turbine for unplanned maintenance). Component failure rates are discussed further in Section 2.2. Activities are also assigned an average duration and logistical requirements in the form of people and vessels needed. For the purposes of COMPASS, activities informed by the evaluation of condition monitoring systems or other relevant component data were not separately distinguished.

There are two modes COMPASS can operate in: "deterministic" and "time-domain based", with the functionality of both highlighted in Figure 1. The time-domain mode has been used for this study. The deterministic mode of the COMPASS model operates by taking failure rate and durations of activities and results in an estimation of the annual usage for personnel and vessels, as well as the farm availability and OPEX. The results can be presented at the lowest level (i.e. per activity and per subsystem for each asset) or can be 'rolled' up into a high-level summary. The time-domain mode calculates the portions of costs, availability and carbon emissions at each time step and then adds them together after calculations at all timesteps are complete. At each time step in the time-domain mode, the COMPASS model checks whether maintenance is required and then checks for availability of personnel and vessels and suitable weather conditions (significant wave height and wind speed). In the case of unplanned maintenance, the Monte Carlo method is applied in order to model failures. The essence of this method is to generate a random number between 0 and 1 and determine whether the component has failed by comparing it to the reliability of component (i.e. the probability of not failing, *R*, in time step *i, R(i)*). If this random number is below *R(i)*, then component has failed, if it is above, the component retains its operational state. Reliability at year (*y*) is estimated from the failure rate of components following equation derived from Thies.[3] Lambda (λ) denotes the number of failures in a given time period.

$$R(y) = e^{-\lambda(y)}$$

Reliability at a timestep *R(i)* is then calculated using the following equation, where *n* is the number of timesteps in a year.

$$R(i) = \sqrt[n]{R(y)}$$

At the end of the simulation, the COMPASS model sums up all the costs from all timesteps associated with O&M activities and adds fixed costs (e.g. computer equipment/software and onshore base costs). In

[2] VGB PowerTech (2014). RDS-PP® Application Guideline Part 32: Wind Power Plants (VGB-S-823-32-2014-03-EN-D).

[3] Thies, P. (2012). Advancing Reliability Information for Wave Energy Converters. Ph.D. University of Exeter. Available from: https://ore.exeter.ac.uk/repository/handle/10036/4053.

addition to all costs, the model calculates total energy produced by the project and calculates both time-based and energy-based availabilities; where time-based availability is the proportion of time that a farm was operational and energy-based availability is the proportion of energy that was generated compared to the ideal case (if the entire project was operating at full capacity 100% of the time). In addition to these conventional outputs, the COMPASS model calculates the overall risk rating associated with each activity and measures carbon emissions emitted by operation vessels which are summed up in the outputs of a simulation.

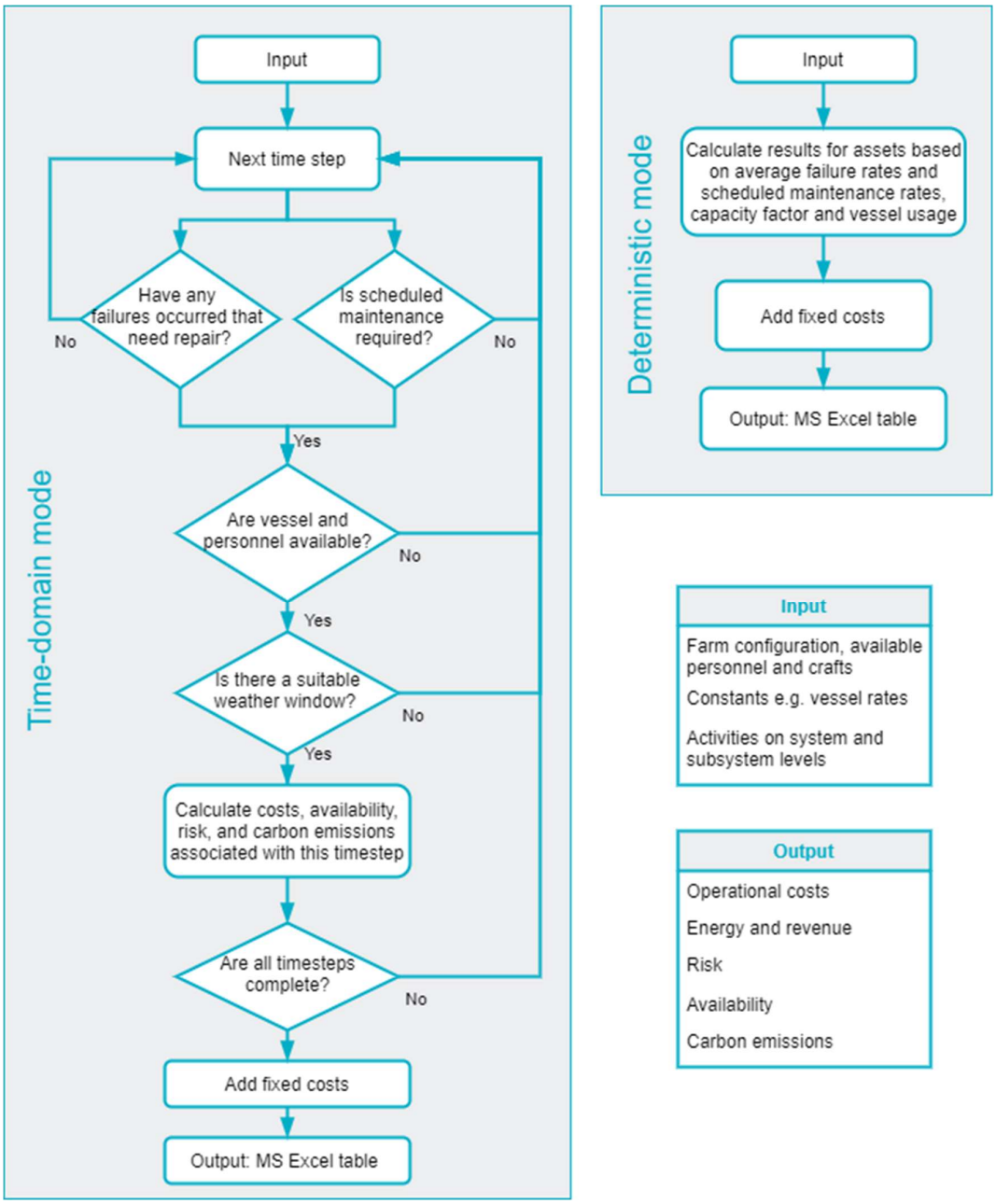

Figure 1: Flow diagrams explaining the two operating modes of COMPASS, the inputs required, and outputs produced

2 Methodology

The COMPASS model requires many different inputs in order to represent the O&M of a floating wind farm as realistically as possible. This section highlights the main inputs that have been used for this study. Some inputs have not been disclosed in this report due to confidentiality, such as specific cost numbers, failure rates and O&M process details.

The stochastic nature of COMPASS, particularly the Monte Carlo method of simulating component failures, means that there is inherent uncertainty in the results. It is therefore necessary to run multiple simulations of each scenario to see an acceptable level of convergence in the results. For this study, we have run twenty simulations of each scenario. All figures are presented with 95% confidence intervals, whereby it can be said with 95% confidence that the true mean of the results lies within that range.

2.1 Site Configuration

The floating offshore wind farms that were modelled were all 495MW projects, consisting of thirty-three 15MW turbines, located off the south west coast of the UK as shown in Figure 2 (alongside weather data points, discussed later in section 2.3). The COMPASS model takes the coordinates of turbines, cables and the port as inputs. Key parameters for the reference sites are stated in Table 1. Port locations (i.e. O&M bases) are discussed in the next section. The three projects are representative of projects expected to be constructed around the year 2030.

Table 1: Key parameters for the three reference sites (all the same unless specified)

Parameter	*Units*	Reference Site
Turbine Rating	*MW*	15
Number of Turbines	*#*	33
Site Capacity	*MW*	495
Water Depth (average)	*m*	CFA1 = 108m CFA2 = 60m CFA3 = 107m
Average Significant Wave Height	*m*	CFA1 = 1.88m CFA2 = 1.95m CFA3 = 2.48m
Average Wind Speed at 100m	*m/s*	CFA1 = 9.94m/s CFA2 = 9.18m/s CFA3 = 9.85m/s
Foundation Type	-	Semi-Submersible
Primary O&M Vessel Type (long term charter)	-	One Service Operation Vessel (SOV) per site
Project Life	*Years*	25

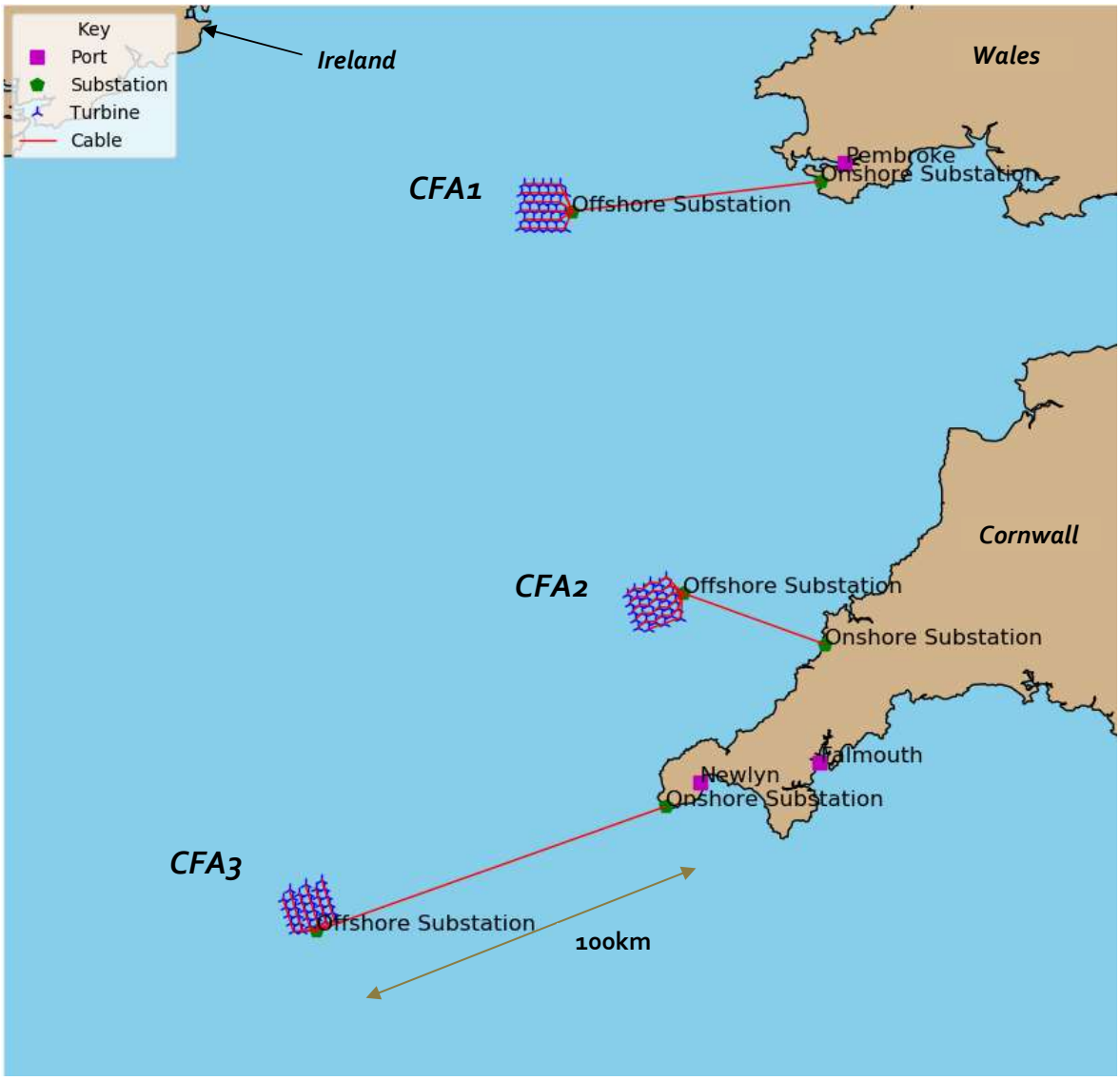

Figure 2: Site map of the three floating wind farms modelled in this study

2.1.1 Port Selection

Three ports were selected for this analysis: Falmouth and Newlyn off the south coast of Cornwall, and Pembroke off the south west coast of Wales. All three wind farms were modelled with the O&M base at each of the three ports in turn, resulting in nine different scenarios. Falmouth Harbour (Figure 3) can provide a wide range of services to commercial shipping including dry docks, bunkers, cargo handling, lay-up berths, commercial moorings and underwater services.[4] Falmouth Harbour is familiar with the offshore renewable energy industry as it is the home of the Falmouth Bay Test Site (FaBTest) for wave energy devices. Newlyn Harbour (Figure 4) is the smallest of the three ports, although it is regarded as

[4] Falmouth Harbour website: https://www.falmouthharbour.co.uk/shipping/.

one of the largest fishing ports in the UK.[5] Pembroke Port (Figure 5) is a busy UK cargo port based on the west coast of Wales. Pembroke Port handles bulk, breakbulk, project and heavy lift cargoes, deliver a twice daily ferry service to Ireland, and act as a layover and supplies hub for west coast shipping.[6] As part of the Port of Milford Haven, Pembroke Port is establishing itself as an offshore renewable energy hub for south west Wales and projects in the Celtic Sea. It is assumed that all three ports can handle any vessel supporting the O&M phase of a floating wind farm.

Figure 3: Falmouth Harbour (Source: cruisemapper.com)

Figure 4: Newlyn Harbour (Source: cornwalls.co.uk)

[5] Newlyn Harbour website: https://www.newlynharbour.com/.
[6] Pembroke Port website: https://www.pembrokeport.com/.

Figure 5: Pembroke Port (Source: Pembroke Port)

The COMPASS model calculates transit distance of vessels 'as the crow flies' using an assumption of average vessel speed. In this modelling, additional time has been added to any transit in and out of each harbour to account for slower speeds when negotiating the estuary and any headlands. These additional times are shown in Table 2 for the three harbours. These are irrespective of the wind farm involved. For example, vessels travelling out of Falmouth Harbour need to travel around the southern headland of Cornwall before being able to access the wind farms in the Celtic Sea.

Table 2: Additional vessel transit times for each port

Port	Time for Transits, Additional to 'As the Crow Flies' (hours)
Falmouth	3
Newlyn	1
Pembroke	0.5

2.2 Floating Wind O&M Activities

Within the full range of assets and subsystems at a floating offshore windfarm there is a large taxonomy of O&M activities. We have assumed that all repairs and maintenance in the farms are to be carried out offshore (i.e. floating turbines are not towed into harbour). Several of the tasks associated with the wind turbine itself are directly transferable from traditional bottom-fixed equivalents, with no major design modifications to components expected aside from the tower and controller software.[7] However, with floating turbine turbines having increased inclinations and complexity in loading, more frequent maintenance visits may become apparent in the future. There are also components that are unique to floating wind, such as the floating substructure, mooring lines, anchors, and dynamic cables. Component failures rates, which affect the frequency of repairs (i.e. unplanned maintenance) in the COMPASS

[7] Carbon Trust, "Floating Wind Joint Industry Project - Phase II summary report," 2020. Available from https://www.carbontrust.com/resources/floating-wind-joint-industry-project-phase-2-summary-report.

model, were originally built up for bottom-fixed offshore wind farms using a combination of publicly available sources (particularly Carroll et al., 2016, and the System Performance, Availability and Reliability Trend Analysis (SPARTA) Portfolio Review 2016, see Figure 6) as well as from the experience of the team at ORE Catapult.[8, 9] It is more difficult to obtain failure rate data for floating wind turbines due, in part, to limited deployment to date.

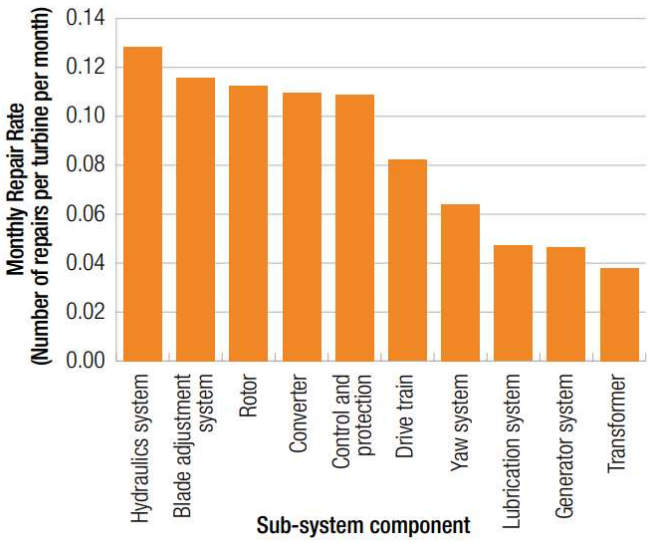

Figure 6: Comparison of subsystem monthly repair rates for bottom-fixed offshore wind turbines (Source: SPARTA Portfolio Review 2016, ORE Catapult)

The reference O&M activities for the floating wind farm are summarised in terms of average annual duration (i.e. annual rate multiplied by activity duration) in Figure 7. To give an impression of the baseline O&M activities modelled in this study, selected examples from separate domains on the windfarm are described in further detail in this section, as follows:

- External turbine O&M – rotor system
- Internal turbine O&M (nacelle) – generator
- Subsea O&M – array cable
- Subsea O&M – mooring systems

[8] Carroll, J., McDonald, A. and McMillan, D. (2015). Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines. Wind Energy, 19(6), pp.1107-1119.
[9] SPARTA (2017) SPARTA Portfolio Review 2016. Available from: https://ore.catapult.org.uk/wp-content/uploads/2018/02/SPARTAbrochure_20March-1.pdf.

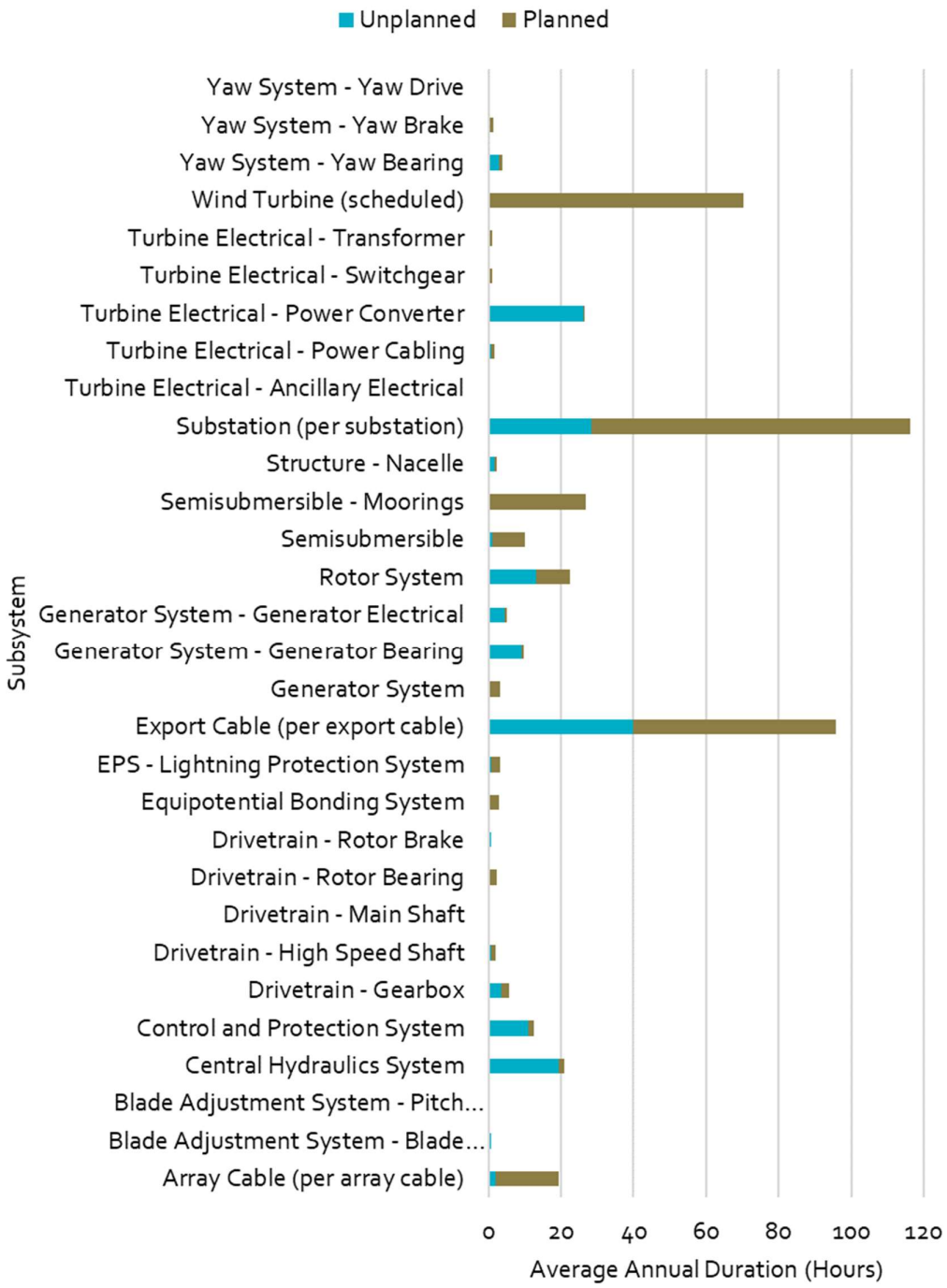

Figure 7: Assumed average annual duration of floating wind O&M activities in each subsystem (per turbine, unless stated otherwise. Farm surveys omitted)

2.2.1 Rotor System

The wind turbine rotor is one of the most critical components within offshore wind O&M due to longer downtime and cost of repair.[10] Initial inspection of the wind turbine blades is carried out either by rope access technicians (see Figure 8), drones or from ground-based camera (either located on the transition piece or vessel).[11] Different windfarms will employ different strategies or combination of these methods, with rope access obviously a task of high-risk consequence. Recent industry engagement suggests a transition from an inspection of the blades every three years to biannually.

Across all methods it was assumed a minimum of two relevant personnel would be required to access the turbine by vessel. With the time it takes to transit, the necessary set-up and the length of modern blades, only one turbine is anticipated to be inspected per day using rope access, with ground-based solutions faster at three turbines a day and drones the fastest at five turbines per day. Some drone inspection providers have been able to carry this out faster with enhanced automation, but with other limiting factors and increasing turbine size this assumption for piloted drone inspections was maintained. For this study, it was also assumed the internal blade inspections would be carried out by rope access. Currently, wind turbine blade repair tasks or upgrades can only be carried out by a human technician. This can be carried out using rope access and, if the damage is sufficiently minor, the rope access technician could make the necessary repairs on the same inspection visit, but this is not included for consideration within COMPASS. If the damage requires structural repair, a repair platform may be utilised. For conventional offshore wind turbines, removing or replacing the blade requires the use of a heavy-lift jack-up vessel (or floating heavy lift vessel, HLV, depending on water depth) and many more technicians.

Figure 8: Rope access technician examining a wind turbine blade (Source: Orbis Energy)

[10] D. Cevasco, S. Koukoura, and A. J. Kolios, "Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications," Renew. Sustain. Energy Rev., vol. 136, no. September 2020, p. 110414, 2021. Available from 10.1016/j.rser.2020.110414.

[11] BVG Associates (2019). Guide to an offshore wind farm. Updated and extended. Available from: https://ore.catapult.org.uk/?industryreports=guide-to-an-offshore-wind-farm.

2.2.2 Generator

One of the main wind turbine components located within the nacelle is the generator. Typical inspection duties include checking the overall alignment (adjusting if required) and examining the generator bearing. As with many scheduled inspections, a team of two or three (one or more specialist and one lower in hierarchy) undertake these duties which can take from four hours up to one day per turbine, depending on the nature of the task. For specific electrical work, authorised technicians (such as contractors) will be utilised. Repair tasks typically last a few days and, similar to the wind turbine blades, a jack-up vessel (e.g. Figure 9) or floating heavy lift vessel is required for a full generator replacement.

Figure 9: Seajacks' jack-up vessel Scylla (Source: offshorewind.biz)

2.2.3 Array Cables

Unlike topside activities, the personnel and vessels involved can vary considerably for subsea intervention. For the case of array cables, scheduled inspection is carried out to determine if the cables have issues with burial, scour or if any other damage can be initially assessed. Conventionally this involves the use of a manned survey vessel with three specialist personnel onboard. It is assumed within COMPASS that this team can survey three array cables per day without asset downtime. For a more accurate assessment of cable exposure or damage a further unscheduled subsea inspection may be required. This can either be carried out using a tethered Remotely Operated Vehicle (ROV) or with a team of divers. However, due to cost, deeper waters and Health and Safety (H&S) risk, diving operations tend only to be carried out in exceptional circumstances at contemporary windfarms. ROV operations involve the use of a specialist support vessel (e.g. Figure 10) that can crane the vehicle into the water. It is assumed that a team of four (of differing grades) would be able to inspect a cable in half a day with an observation class ROV. Repair of the array cable may be required at the turbine/substation end with the team of three authorised accessing by a transfer vessel (i.e. Crew Transfer Vessel, CTV, or Service Operation Vessel, SOV) and taking on average three days for repair. For damage imparted elsewhere, a large specialist vessel (e.g. Cable Lay Vessel, CLV) is required to remove a section of cable from the seabed, repair (jointing) and rebury. A larger technician team is assumed to take five days with, on

average, three turbines shut down for the duration of work, but this could potentially take longer. A similar vessel would be required for complete replacement of the array cable.

Figure 10: ROV launched from support vessel (Source: ferri-sa.es)

2.2.4 Mooring Systems

Semi-submersible platforms for offshore wind turbines commonly use catenary moorings with drag-embedment anchors, although other moorings systems are available. Taking ORE Catapult's expertise and available literature into account, annual (once a year) and special surveys (every five years) will be required for catenary moorings.[12] The floating wind farm in this study assumes this mooring configuration not only because it has been the most commonly deployed to date, but also because there is more publicly available reliability and maintenance data for this than for other options.

The annual survey is assumed to be carried out with an observation ROV to visually check the condition of all moorings. For a special survey (i.e. once every five years) it is recommended where possible to raise moorings to the surface for a more detailed inspection. It is assumed that half of the special surveys will be carried out with a vessel onto which a mooring will be raised, and the other half with an observation ROV (i.e. subsea). Future floating platforms are expected to use hybrid mooring systems which is a combination of chain and synthetic moorings. Periodic inspections of moorings may involve checking an angle of the catenary mooring to estimate the changes in tension, which can also be done by an observation ROV. Anchors are expected to be inspected together with the moorings, as anchor failure rates are very low and so do not require any additional planned inspection.

Synthetic moorings are expected to be used in future floating turbine assemblies, given ongoing technology improvements regarding their physical properties and performance attributes. Synthetic moorings can be damaged by contact with the seabed, therefore a hybrid system is considered, similar

[12] Kai-Tung, M. et al. (2019) Chapter 12 - Inspection and monitoring, Mooring System Engineering for Offshore Structures, Gulf Professional Publishing, Pages 233-253, ISBN 9780128185513, Available from: https://www.sciencedirect.com/science/article/pii/B9780128185513000120.

to that discussed in Borg et al. (2020).[13] Full mooring length for catenary systems can be approximately four to six times the water depth (in certain site conditions). Therefore, to make conservative estimations a value of six was chosen, with one sixth consisting of synthetic rope and the rest chain composition (although this composition would vary site-to-site). For remediation of a mooring failure, it is assumed that the entire mooring together along with the anchor are replaced using an Anchor Handler Tug Supply vessel (AHTS). The cost of a replacement was estimated using the cost per meter (for both chain and synthetic rope) multiplied by the mooring length, plus the cost of a new drag-embedded anchor.[14] If an anchor fails, both the anchor and the mooring are expected to be replaced even if the mooring itself did not fail. However, this mooring may then be reused in other projects (e.g. testing or less load-intensive deployments).

Figure 11: DOF's Anchor Handler Tug Supply vessel Skandi Vega (Source: offshore-energy.biz)

The synthetic mooring failure rate was estimated from a DTOcean+ report.[15] This was combined from the "Polyester rope", two "Connectors" and "Other" components' failure rates, assuming that the chain part of the mooring does not contribute significantly to its failure rate (as a large proportion of the chain will lie on the seabed where the tension is significantly lower than in the hanging section of the mooring). This resulted in a failure rate estimation of 0.0017 failures per year, which is lower than typically assumed for a chain mooring. This was expected as synthetic ropes are resistant to corrosion and have a much

[13] Borg, M. et al. (2020) Technical Definition of the TetraSpar Demonstrator Floating Wind Turbine Foundation. Energies. [Online] 13 (18), 4911. Available from: http://dx.doi.org/10.3390/en13184911.
[14] Rhodri, J., Marc, C. R. (2015) Floating Offshore Wind: Market and Technology Review, Carbon Trust, Available from: https://www.carbontrust.com/resources/floating-offshore-wind-market-technology-review.
[15] DTOcean+ (2015). Deliverable 4.6 - Framework for the prediction of the reliability, economic and environmental criteria and assessment methodologies for Moorings and Foundations. Available from: https://www.dtoceanplus.eu/content/download/2525/file/DTO_WP4_ECD_D4.6.pdf.

greater fatigue life (chain mooring failure rate is 0.0025-0.00378).[16, 17] The anchor failure rate was taken from a reliability study of drag embedment anchors.[18]

2.3 Weather Time-Series Data

In order to run the time-domain mode of COMPASS, a dataset of time-series weather data is required. For this study, we have extracted hourly weather data for the reference site from the European-funded Copernicus project, which provides free climate reanalysis data.[19] ORE Catapult has developed a Python-based script to enable easy extraction of the ERA5 dataset, a climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).[20] The data is available in hourly intervals from 1950 to the present day and contains the parameters required to assess power output and operational accessibility (i.e. significant wave height, wave energy period and wind speed). The spatial resolution of the ERA5 data is 0.5 decimal degrees, meaning that data can only be extracted at certain points (approximately 50 km apart at the project latitudes being considered).

The three data points selected for this study are all an acceptable distance from the wind farms, as shown previously in Figure 2, and the selected data runs from 1990 to 2019. As the lifetime of the reference wind farm is twenty-five years, only the data covering 1990 to 2014, inclusive, were used.

2.4 Vessel Fleet and Personnel Availability

In order to calculate the operational expenditure and live emissions (i.e. from fuel burnt in vessels) of the scenarios simulated by COMPASS, inputs are required to characterise the vessels involved in the O&M activities. Realistic vessel charter rates are difficult to obtain due to commercial sensitivities. ORE Catapult has leveraged the 4C Offshore 'Wind Farm Service Vessels' database to gain a greater understanding of the types of vessels used for offshore wind O&M.[21] The database has been used to corroborate the input assumptions of vessel specifications such as average speed, operational weather limits, personnel capacity and fuel consumption. Access to this data also provided direct confirmation of the subcategories of vessels utilised at specific windfarms for different scenarios and environmental

[16] Weller, S.D. et al. (2015). Synthetic Mooring Ropes for Marine Renewable Energy Applications. Renewable Energy, Volume 83, Pages 1268-1278, ISSN 0960-1481. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0960148115002402.
[17] Fontaine, E. et al. (2014) Industry survey of past failures, pre-emptive replacements and reported degradations for mooring systems of floating production units. Offshore Technology Conference. Available from: https://onepetro.org/OTCONF/proceedings-abstract/14OTC/4-14OTC/D041S047R002/172127.
[18] Moharrami, M. & Shiri, H. (2018). Reliability of drag embedment anchors for applications in Canadian deep offshore.
[19] Copernicus (2021). ERA5 hourly data on pressure levels from 1979 to present. Available from: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview.
[20] ORE Catapult (2021). Extracting and Using Weather Time-Series Data for Offshore Renewable Energy Projects. Available from: https://ore.catapult.org.uk/analysisinsight/weather-time-series-data-in-offshore-renewables/.
[21] 4C Offshore (2021). Subscribe to our Wind Farm Service Vessel Information. Available from: https://www.4coffshore.com/subscriptions/wind-farm-service-vessels/.

conditions, not typically disseminated into the public domain. A vessels database from the DTOcean+ project has also been used, primarily to inform assumptions for AHTS vessels.[22]

The base case for this analysis assumes that one SOV is available on a long-term basis for the wind farm (with an annual fee of £6.57m from an estimated day rate of £18,000), whilst other specialist vessels (e.g. HLV, AHTS vessel) can be chartered on an ad-hoc basis. The SOV returns to the O&M base every two weeks to resupply. It is assumed that technicians can be contracted for short-term work, to supplement full-time office staff at the O&M base. The day rate for a contracted technician varies depending on the level of seniority/qualifications required for specific O&M tasks, as shown in Table 3.

Table 3: Assumptions for day rates of offshore personnel (Source: ORE Catapult)

Technician Type	Assumed Day Rate *(£/day)*
Labourer	300
Technician	400
Skilled Technician	500
Rope Access Technician	500
Authorised Technician	600
Specialist	700
ROV Technician	550
Diver	700

2.4.1 Vessel Emissions

Emissions caused by industry are becoming an area of increasing scrutiny, particularly in the year of COP26, where much of the focus is on national endeavours to reach 'net zero' emissions.[23] For example, the UK has a target to become net zero by 2050, with Scotland targeting an earlier date of 2045. While offshore wind is well regarded as a low carbon form of energy, especially compared to fossil fuel sources like coal and natural gas, 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. The COMPASS model is capable of giving estimates of the emissions produced from vessels during the O&M phase. Vessel emissions are most commonly presented in terms of emissions intensity, meaning the actual emissions divided by the energy production of the farm.

[22] DTOcean+ (2020). Deliverable D5.7 - Logistics and Marine Operations Tools - Alpha Version. Available from: https://www.dtoceanplus.eu/Publications/Deliverables/Deliverable-D5.7-Logistics-and-Marine-Operations-Tools-alpha-version.
[23] UN Climate Change Conference UK 2021 (COP26) website: https://ukcop26.org/.

Calculating vessel emissions in COMPASS relies on making assumptions on fuel consumption during three different phases of activity. In the case of an SOV, these are:

i) Transit (from port to/from site and between turbines),

ii) In Dynamic Positioning (DP) mode (supporting a personnel-to-turbine transfer) and,

iii) Standby mode (either offshore or in port).

For this study, it is assumed that a SOV consumes 720 litres/hour in transit mode, 375 litres/hour when in DP mode, and 120 litres/hour when standing by (which is likely to include periods of full engine shutdown). These values have been defined using ORE Catapult expertise and industrial contacts. It is assumed that the SOV operates with Marine Gas Oil (MGO) which produces 2.775 kg of carbon dioxide equivalent (CO_2e) per litre when combusted (according to UK Government documentation).[24]

[24] UK Government (2019). Greenhouse gas reporting: conversion factors 2019. Available from: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019

3 Key Results

3.1 Operational Expenditure and Availability

The COMPASS model provides an estimate of the average operational expenditure (OPEX) incurred annually at the floating offshore wind farms. The OPEX outputs of the current COMPASS version include:

- Total annual vessel charter fees.
- Total annual personnel costs.
- Total annual fixed costs – includes marine coordination, onshore base (e.g. rent, electricity, heating), training, personal protective equipment (PPE) and software licences (e.g. control systems).

The outputs do not include other elements of OPEX, such as seabed leasing, operational insurance and the cost of spare parts.

The mean values from the simulations for annual OPEX are shown in Table 4. Site 1 has the highest OPEX of all three sites when the O&M base is located at either Falmouth or Newlyn. This is to be expected given the transit distance involved (i.e. site 1 is off the south west coast of Wales, whilst Falmouth and Newlyn are both off the south coast of Cornwall). Conversely, when Pembroke Port is used as the O&M base, site 3 has the highest OPEX (again due to having the greatest transit distance). It should be noted that site 3 was expected to have the highest OPEX given the more severe weather conditions (see Figure 12). More severe weather conditions would result in vessels spending longer waiting for an available weather window for carrying out operations, but still being paid for if chartered on a day rate basis). However, site 3 is the most cost-effective site when the O&M base is at Falmouth or Newlyn (particularly Newlyn, with approximately £600,000 less annual OPEX than site 1). These results suggest that transit distance is a more important factor than weather conditions, although it should be pointed out that the differences in weather are small between the sites (e.g. 2.5m average significant wave height, Hs, at site 3 vs 1.9m average Hs at site 1).

Table 4: Annual OPEX, mean values, for the nine scenarios

Annual Operational Expenditure (£m)			
Site > **Port v**	CFA1	CFA2	CFA3
Falmouth	19.0	18.8	18.6
Newlyn	19.2	19.0	18.6
Pembroke	18.7	18.7	18.9

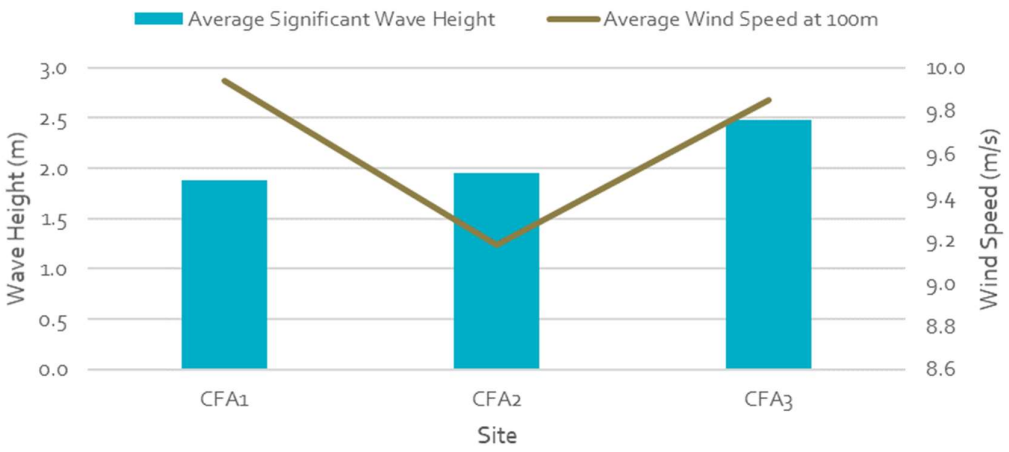

Figure 12: Average weather conditions at the three sites

It is also useful to present OPEX in terms of per kW of installed capacity, as this enables comparison to other studies. The OPEX per kW mean values are shown in Table 5, with graphical representation alongside the 95% confidence intervals in Figure 13 (site 1), Figure 14 (site 2) and Figure 15 (site 3). The main area of uncertainty in this analysis can be traced to the O&M vessels (shown by the 95% confidence intervals), relating to those vessels chartered on an ad-hoc basis. For example, component failures that require a large, high-cost floating HLV have low failure rates, so will not have occurred in all twenty simulations.

The floating wind sector is still at an early stage of development, with demonstration and pre-commercial projects currently operating and being constructed. Therefore, any annual OPEX estimations of the full lifecycle of a commercial-scale floating wind farm come primarily from other modelling studies, rather than real site data. The Carbon Trust published a report in 2015 which suggested that floating wind farms would incur annual OPEX of £200/kW at the prototype stage, £140/kW at pre-commercial level, and £90/kW when full commercial scale is achieved.[25] The commercial level farm is the most comparable to the CFA sites, but the £90/kW estimate is much higher than the ~£38/kW in this study (although our estimates omit seabed leasing, operational insurance, and the cost of spare parts). A possible explanation of this is that industry knowledge has expanded significantly since 2015 and the sector has grown at a much more accelerated pace than was expected. A more recent study by the US National Renewable Energy Laboratory (NREL) suggests much lower OPEX values for a 600MW floating wind farm, ranging from $84/kW (i.e. £59/kW at $1.42 to £1 exchange rate) down to $38/kW (i.e. £27/kW) as deployment increases.[26] This large range in estimations highlights the uncertainty involved in modelling an early-stage technology such as floating wind. For further reference, the "Guide to an offshore wind farm"

[25] The Carbon Trust (2015). Floating Offshore Wind: Market and Technology Review. Available from: https://www.carbontrust.com/resources/floating-offshore-wind-market-technology-review.
[26] Musial, W., Beiter, P. & Nunemaker, J. (2020). Cost of Floating Offshore Wind Energy Using New England Aqua Ventus Concrete Semisubmersible Technology. Available from: https://www.nrel.gov/docs/fy20osti/75618.pdf.

(published on behalf of ORE Catapult and the Crown Estate) estimated total OPEX (i.e. including spare parts and operational insurance) of a bottom-fixed offshore wind farm to be approximately £75/kW.[11]

Table 5: Annual OPEX per kW, mean values, for the nine scenarios

Annual Operational Expenditure (£/kW)			
Site > Port v	CFA1	CFA2	CFA3
Falmouth	38.3	38.0	37.5
Newlyn	38.7	38.3	37.5
Pembroke	37.7	37.7	38.2

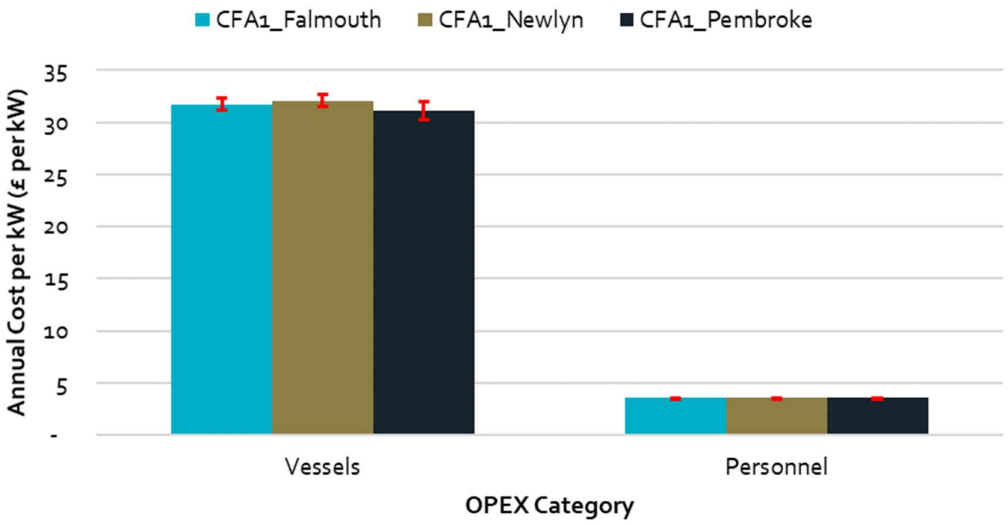

Figure 13: OPEX breakdown for site 1 at the three different ports, fixed costs not shown

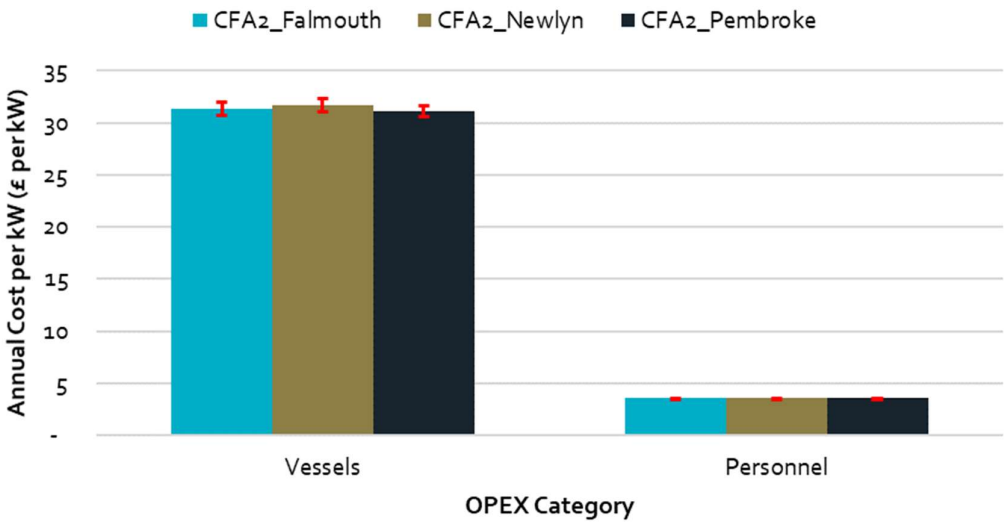

Figure 14: OPEX breakdown for site 2 at the three different ports, fixed costs not shown

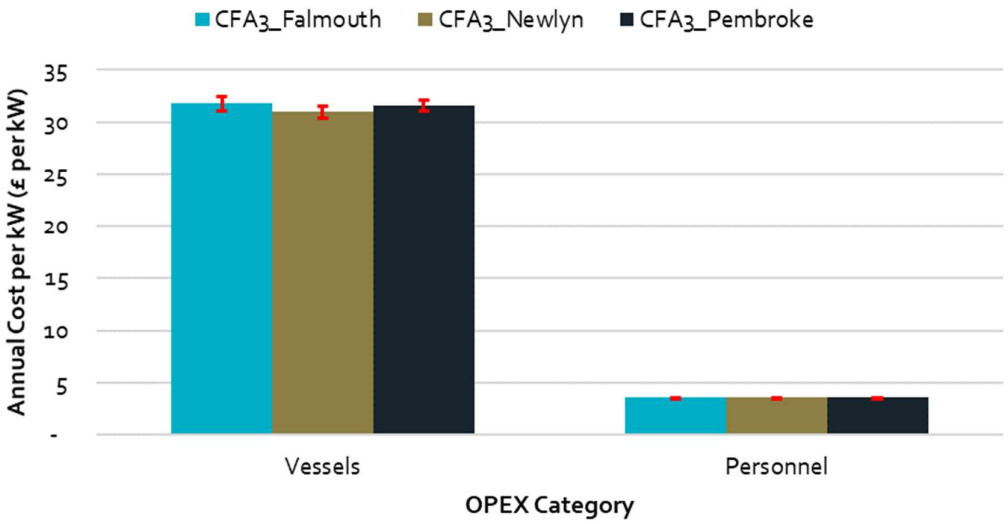

Figure 15: OPEX breakdown for site 3 at the three different ports, fixed costs not shown

Another important Key Performance Indicator (KPI) to consider is the availability of the wind turbines at site. Availability can either be defined as time-based or energy-based. Time-based availability is the most commonly used KPI and is calculated in COMPASS as a percentage of the operational turbine hours divided by the available hours in a year. The value is averaged across all turbines and all years to produce the time-based availability for the whole project as a single percentage. Energy-based availability (also referred to as production-based availability, PBA) is similar, however, it is defined as the actual Annual Energy Production (AEP) of the turbines divided by the potential energy generated. This is distinguishable from time-based availability as it recognises that not all time periods result in the same

potential energy production. For example, an hour of turbine downtime during winter, when wind speeds are generally higher, will result in more lost production compared to an hour of downtime in summer.

The results of availability for the reference sites are shown in Table 6 (time-based availability), Table 7 (energy-based availability), and Figure 16 (graphical with 95% confidence intervals shown). The impact of weather conditions are shown more clearly here, with site 3 (with the highest Hs) having the lowest availability regardless of the location of the O&M base. This is primarily due to there being fewer weather windows (periods of calm weather allowing vessels to access the site). The negative impact of this is mitigated for site 3 when the O&M port is located at Newlyn Harbour, the site's nearest port. Similarly, availability is highest at site 1 when the O&M based is located at Pembroke Port (it's nearest port in this analysis). The best port for site 2 looks to be Newlyn Harbour, if judged solely on availability. However, the highest OPEX at site 2 was also found to be when the O&M base was located at Newlyn Harbour, although only by £300,000 per year when compared to Pembroke Port. In context this seems like a small difference, given that the charter rate of a floating HLV is typically £200,000-£300,000 per day. The uncertainty in the vessel costs (shown by the overlapping 95% confidence intervals in Figure 14) mean that Newlyn Harbour may be the best port for site 2 after considering the revenue earned from increased turbine availability.

This example highlights the need to consider many factors and sensitivities when judging wind farm performance and identifying the optimal O&M logistics strategy. The energy-based availability estimates correspond well with bottom-fixed turbines as published in the SPARTA portfolio review 2019/20.[27]

Table 6: Time-based availability, mean values, for the nine scenarios

Time-Based Availability			
Site > **Port v**	CFA1	CFA2	CFA3
Falmouth	96.9%	97.0%	94.8%
Newlyn	97.0%	97.1%	95.1%
Pembroke	97.2%	96.9%	94.5%

Table 7: Energy-based availability, mean values, for the nine scenarios

Energy-Based Availability			
Site > **Port v**	CFA1	CFA2	CFA3
Falmouth	96.5%	96.5%	94.0%
Newlyn	96.6%	96.6%	94.3%

[27] SPARTA System Performance, Availability and Reliability Trend Analysis (2020). Portfolio Review 2019/20. Available from: https://ore.catapult.org.uk/wp-content/uploads/2021/02/SPARTA-Review-2020.pdf.

Pembroke	96.8%	96.4%	93.7%

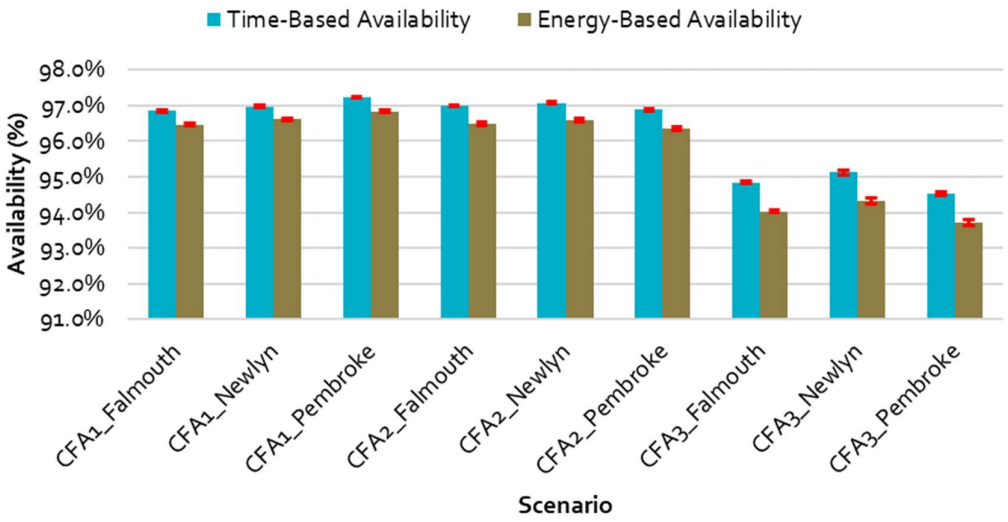

Figure 16: Availability comparison for the nine sites

Other KPIs to consider are AEP (see Figure 17) and the site capacity factor (i.e. AEP actually generated divided by the maximum theoretical power possible). Capacity factor differs from energy-based availability because the maximum theoretical power doesn't consider weather conditions (i.e. it is simply the site capacity multiplied by the number of hours in a year). The trends (Table 8) are the same as seen in the availability outputs; site 1 has its higher capacity factor when the O&M base is at Pembroke Port, whilst an O&M base at Newlyn Harbour gives the highest capacity factors for site 2 and 3.

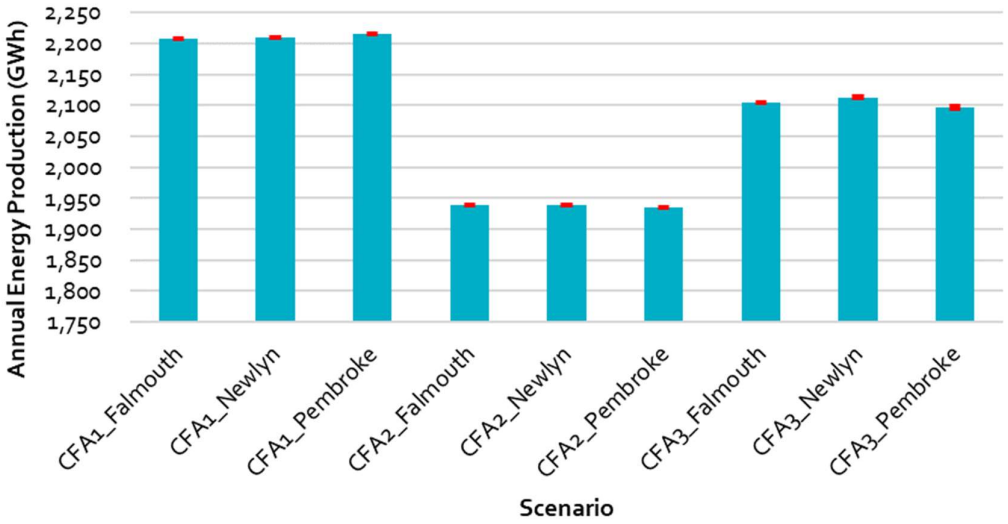

Figure 17: AEP comparison for the nine sites

Table 8: Capacity factor excluding losses, mean values, for the nine scenarios

Capacity Factor (Excluding Losses)			
Site > / Port v	CFA1	CFA2	CFA3
Falmouth	50.85%	44.67%	48.50%
Newlyn	50.93%	44.70%	48.70%
Pembroke	51.07%	44.59%	48.32%

3.2 Vessel Usage and Personnel Transfers

It is useful to understand how often different types of vessels are required for supporting O&M activities, particularly as this may inform port requirements. The COMPASS model produces outputs for annual usage of each vessel at the floating wind farm. Figure 18 presents an example of these outputs for site 1 with the O&M port at Falmouth Harbour. This is representative of the other scenarios and shows that the three most utilised vessel types are SOV, survey vessel and ROV support vessel. All vessels apart from the SOV are assumed to be chartered on an ad-hoc basis, meaning that they can be made available for other projects. The SOV is assumed to stay at that particular site. Therefore, when the SOV is not in either transit or working (i.e. DP) mode, then it is in standby mode as shown in Figure 19. In reality, it is likely that the SOV would be shared with other projects in the area and possibly leased on an ad-hoc or summer-only basis. Survey vessels and ROV support vessels would regularly be used at the site and would require appropriate berths at port when leased for O&M activities. The larger vessels (e.g. HLVs, CLVs) would also be used for the CFA sites, albeit less frequently. Nevertheless, an appropriate berth would still be required at the port during these activities. Note that rock dumping vessels and anchor handlers are involved in O&M (as modelled), although usage is minimal.

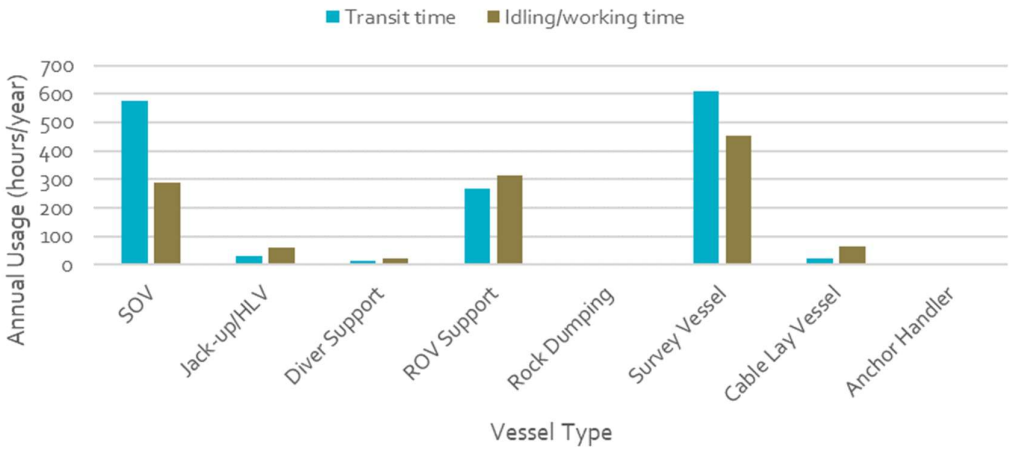

Figure 18: Vessel usage estimates for site 1 with Falmouth Harbour as the O&M base

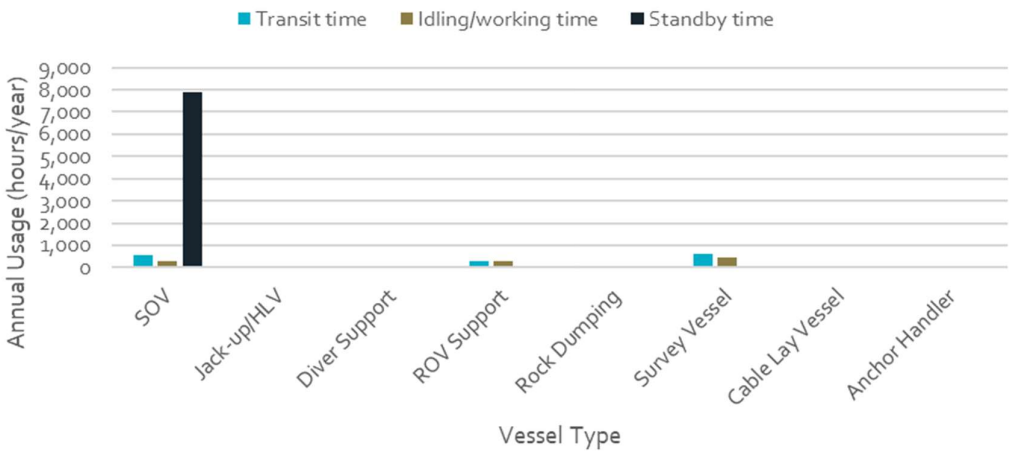

Figure 19: Vessel usage estimates for site 1 with Falmouth Harbour as the O&M base, when SOV standby time is included

Personnel transfers occur when technicians are transported from a vessel (a SOV in the scenarios in this study) onto a turbine in order to carry out O&M activities. The COMPASS model records the average number of annual transfers of personnel, which can be a useful metric for understanding vessel usage further, as well as aspects of H&S (vessel transfers are one cause of H&S incidents, as reported by G+).[28] The COMPASS simulations for the nine scenarios estimate that between 1,309 to 1,314 personnel-to-turbine transfers take place annually at each site, equating to approximately 109 transfers per month. With a wind farm of thirty-three turbines, this equates to an average of 3.3 personnel-transfers per turbine per month. This is lower than recorded in the SPARTA portfolio review 2019/20, where personnel-transfers per turbine have decreased from around 11 per month in 2014-25 to around 7 per month in 2019-20. One explanation for this is the optimisation functionality inherently in the COMPASS model, whereby O&M activities are grouped together to minimise personnel transfers.

Table 9: Annual personnel transfers, mean values, for the nine scenarios

Annual Personnel Transfers			
Site > **Port v**	CFA1	CFA2	CFA3
Falmouth	1,312	1,314	1,311
Newlyn	1,311	1,313	1,310
Pembroke	1,313	1,316	1,309

[28] G+ Global Offshore Wind Health & Safety Organisation (2020). 2020 incident data report. Available from: https://www.gplusoffshorewind.com/__data/assets/pdf_file/0010/853246/G-Plus-Global-Offshors-Wind-Health-and-Safety-Organisationjk.pdf.

3.3 Vessel Emissions

The inputs of fuel consumption and emissions per litre, combined with the vessel usage statistics produced by COMPASS, result in the annual SOV emissions estimates shown in Table 10. These absolute emissions can be divided by the AEP of the wind farms to estimate SOV emissions intensity (see Table 11), which is a more comparable metric to other studies. The annual SOV emissions intensity estimates range from 1.7kg CO_2e/MWh to 2.0kg CO_2e/MWh. These correspond well to data published by Ørsted, a leading developer of bottom-fixed offshore wind farms, where figures from 2020 conclude that 1.6kg CO_2e/MWh were produced during crew transport and service vessel operations.[29, 30] The result also corresponds well to another study by ORE Catapult (estimated at 2.1kg CO_2e/MWh for a bottom-fixed wind farm with 100 turbines, 130km from shore).[31] However, it is much lower than Ørsted's data for 2019 (3.5kg CO_2e/MWh).[32, 33] This uncertainty suggests that there is inherent variation in these values, and that further work (including real-world monitoring of SOV emissions) is required to benchmark the vessel emissions outputs of COMPASS. It should be noted that ongoing development of alternative fuels, including fully electric SOVs, is expected to significantly reduce or even remove live emissions (but not embodied carbon) related to O&M vessels. The breakdown of SOV emissions intensity by operation mode is given in Figure 20, and an example estimate of emissions intensity of other O&M vessels is shown in Figure 21 for site 1 with Falmouth Harbour as the O&M base.

Table 10: Annual SOV emissions, mean values, for the nine scenarios

Annual SOV Emissions (kt CO_2e)			
Site > Port v	CFA1	CFA2	CFA3
Falmouth	4.08	3.76	3.96
Newlyn	4.02	3.70	3.85
Pembroke	3.74	3.92	4.21

[29] Ørsted (2020). Sustainability Report 2020. Available from: https://orstedcdn.azureedge.net/-/media/annual2020/sustainability-report2020.ashx?la=en&rev=81afbfd3377a498ca148788a8837380 5&hash=BD138224A56386F72DBDDDD24A9E44DE.

[30] Ørsted (2020). Annual report 2020. Available from: https://orstedcdn.azureedge.net/-/media/annual2020/annual-report2020.ashx?la=en&rev=3f951652f6c243ef83ded864b6b670b2&hash=94C2C2FFBA4837E0D64E8D7CB29C3B38.

[31] ORE Catapult (2021). Setting a benchmark for decarbonising O&M vessels of offshore wind farms. Available from: https://ore.catapult.org.uk/analysisinsight/setting-benchmark-decarbonising-om-vessels-offshore-wind-farms/.

[32] Ørsted (2019). Sustainability Report 2019. Available from: https://orsted.com/-/media/annual2019/Sustainability-report-2019-online-version.pdf.

[33] Ørsted (2019). Summary 2019. Annual report and sustainability report. Available from: https://orsted.com/-/media/annual2019/AR19-EN-Summary-2019.pdf.

Table 11: Annual SOV emissions intensity, mean values, for the nine scenarios

Annual SOV Emissions Intensity (kg CO_2e/MWh)			
Site > / Port v	CFA1	CFA2	CFA3
Falmouth	1.85	1.94	1.88
Newlyn	1.82	1.91	1.82
Pembroke	1.69	2.02	2.01

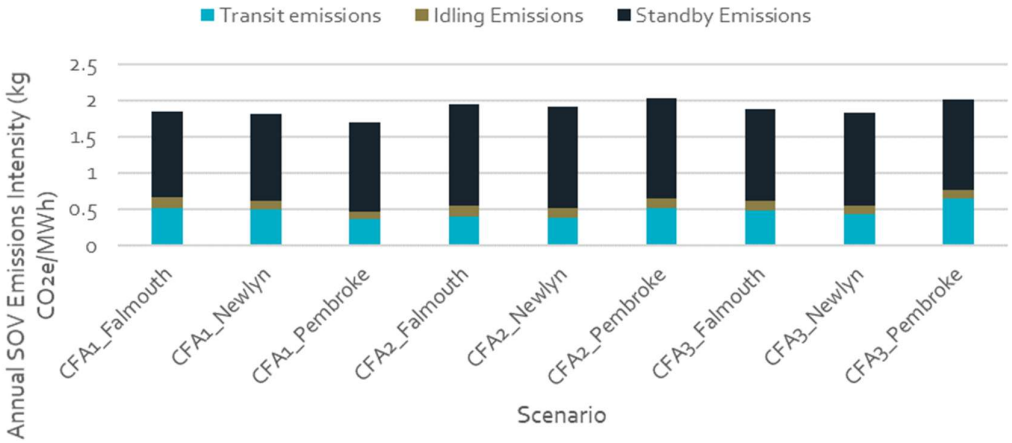

Figure 20: Annual SOV emissions intensity for the nine scenarios, breakdown by operation mode

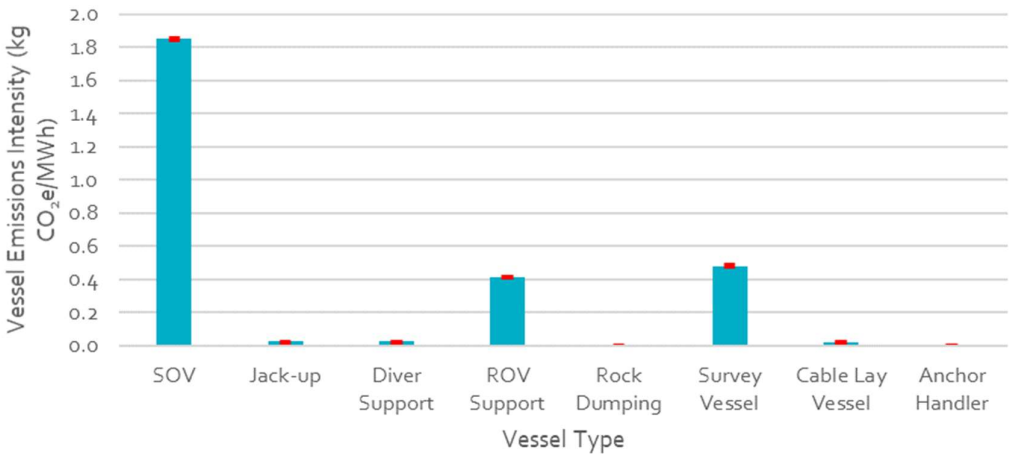

Figure 21: Annual emissions intensity from all O&M vessels for site 1 with Falmouth Harbour as the O&M base

4 Sensitivity Analysis

Two brief sensitivity studies are presented in this section to highlight the uncertainty involved in the O&M simulation modelling.

4.1 SOV Charter Rate

O&M vessel charter rates can vary significantly, and there are many leasing options including ad-hoc or summer-only charters. The offshore wind industry is forecasted to grow hugely in coming years, and this will put increasing strain on all areas of the supply chain, including vessels, which is likely to impact on costs. Vessels typically have higher charter fees during times of peak demand, for example during the summer months when preventative maintenance campaigns are taking place. The base case OPEX results assume that the SOV is on long-term hire at a fee of £6.57m per year (i.e. £18,000 per day). Figure 22 shows the sensitivity of this assumption and the impact on OPEX for the example of site 1 with Falmouth Harbour as the O&M base. In this scenario, if the SOV charter was £8m per year (i.e. a 22% increase) then this increases annual OPEX from £38.3/MW in the base case to £41.2/MW (a 7.6% increase).

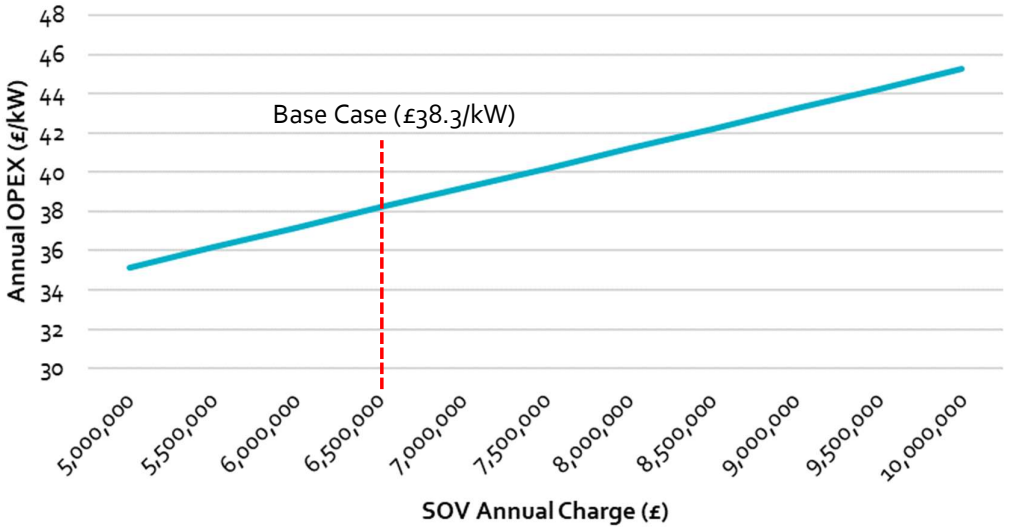

Figure 22: Sensitivity analysis of SOV charter rate at site 1 with Falmouth Harbour as the O&M base

It should be noted that the SOV in each scenario spends the majority of its time in standby mode, stationed offshore. It is therefore possible that the wind farm owner will decide to bring in an SOV for summer preventative maintenance campaigns, which would reduce the annual SOV fee considerably, but risks suitable vessels being unavailable. This will increase costs in other areas (i.e. when emergency corrective maintenance requires ad-hoc vessel hire, and the associated increased turbine downtime) and may not be the most cost-effective solution. Further analysis is required to assess more complex SOV charter arrangements.

4.2 SOV versus CTVs

For wind farms within around 60km from an O&M port, it is common to see Crew Transfer Vessels (CTVs) used as the primary O&M vessel, rather than SOVs. CTVs are much smaller and quicker than SOVs and can transport up to twenty-four personnel to the offshore site (some CTVs are smaller and can only carry twelve personnel). Personnel gain access to turbines by the 'push on' method, where the bow of the CTV engages with an access ladder on the turbine substructure. The technician then essentially has to step across from the CTV onto the ladder. It is a much more high-risk method of turbine access than an SOV 'walk-to-work' gangway and therefore has more restrictions on the operation (i.e. COMPASS typically assumes 2m Hs for CTV transfers and 3.5m Hs for SOV transfers). CTVs are significantly cheaper than SOVs (modelled here as having a £1m annual fee, compared to £6.57m for an SOV). CTVs are also much faster than SOVs (we assume 42kts average speed) but do need to return to the O&M base at the end of every working shift (compared to a SOV which stays offshore for two weeks at a time) and would therefore require a permanent berth at the port. A sensitivity study has been undertaken to assess if two CTVs would be a viable option for the CFA sites as the primary O&M vessels. We have used site 1 as the example, with Pembroke Port (its closest port) as the O&M base.

Figure 23 shows that there is a cost saving caused by using two CTVs on a long-term charter rather than one SOV, as annual OPEX reduces from £18.7m (or £37.7/kW) to £13.8m (£27.8/kW). However, the performance of the farm is reduced, with time-based availability decreasing from 97.2% in the SOV case to 93.9% in the CTV case (see Figure 24), due to the lower operational weather limits of CTVs. This equates to a lower annual energy production (shown in Figure 25), with 2,216GWh generated per year in the SOV case compared to 2,111GWh in the CTV case (which would return a lower revenue). Whilst the cost saving in OPEX from having two CTVs rather than one SOV as the primary O&M vessel is desirable for the wind farm owner, it is likely to be countered by the decreased revenue generated. For the site modelled here, the 'break-even' point, where the revenue lost by having lower AEP equals the OPEX saved, occurs when the sale price of electricity (or strike price) is £49.2/MWh. This strike price is unlikely to be reached for floating wind farms in the near term as, for example, the UK Government's administrative strike price for floating wind in the upcoming Contracts for Difference (CfD) auction round will be £122/MWh.[34] However, ORE Catapult forecasts that the cost of floating wind could come down to around £40/MWh by 2040 if rapid deployment of commercial-scale projects is followed by higher innovation. Therefore, it is possible that CTVs become the preferred choice for some large floating wind farms, but only if there is an O&M port within an appropriate distance from the site.[35]

[34] Department for Business, Energy and Industrial Strategy (2021). Contracts for Difference Scheme for renewable electricity generation. Draft Allocation Framework for the Fourth Allocation Round, 2021. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1016684/draft-allocation-framework-cfd-ar4.pdf.

[35] ORE Catapult (2021). Floating Offshore Wind: Cost Reduction Pathways to Subsidy Free. Available from: https://ore.catapult.org.uk/?orecatapultreports=floating-offshore-windcost-reduction-pathways-subsidy-free.

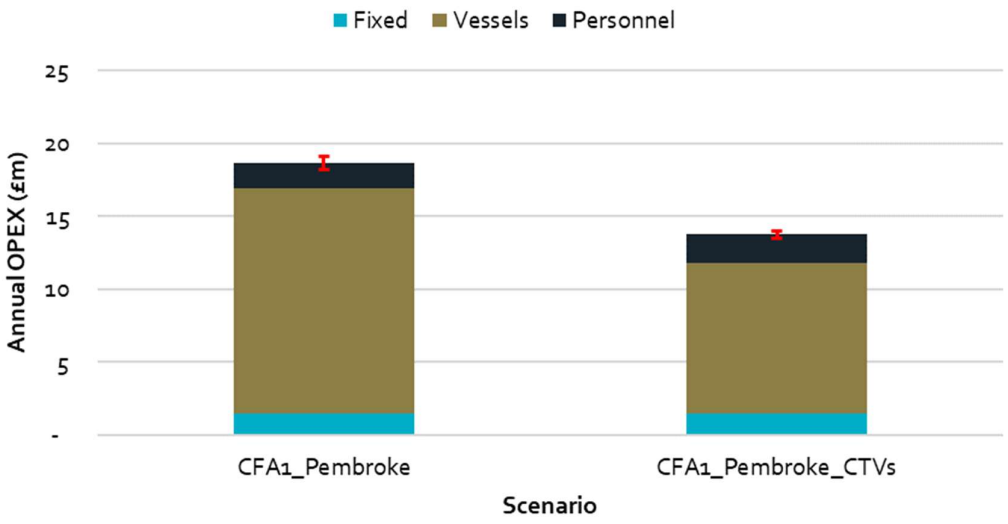

Figure 23: Sensitivity analysis of OPEX for SOV case compared to CTV case, for site 1 with Pembroke Port as the O&M base

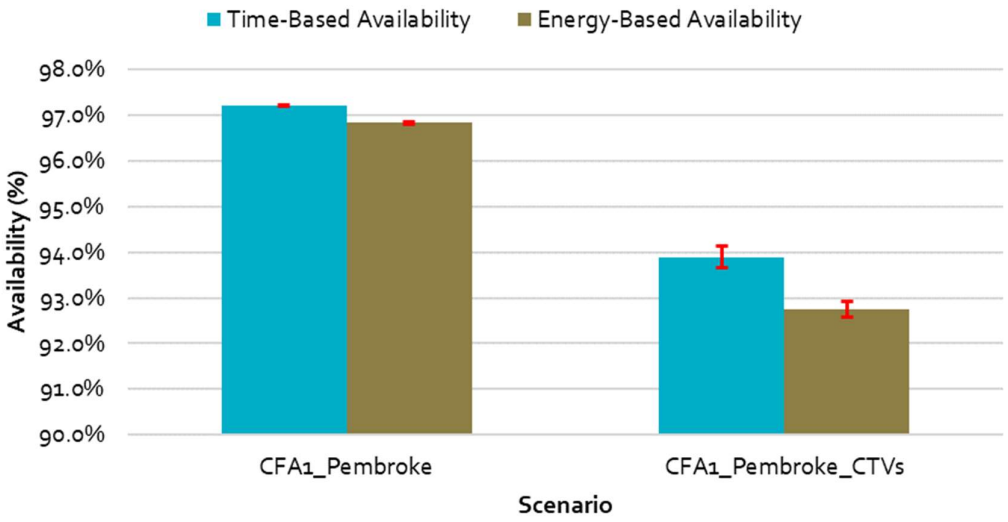

Figure 24: Sensitivity analysis of availability for SOV case compared to CTV case, for site 1 with Pembroke Port as the O&M base

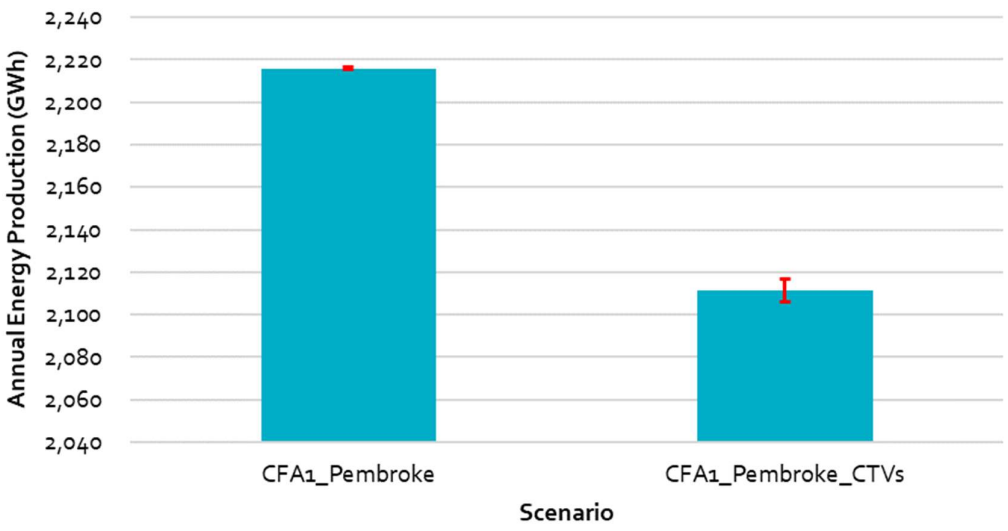

Figure 25: Sensitivity analysis of AEP for SOV case compared to CTV case, for site 1 with Pembroke Port as the O&M base

5 Discussion

The purpose of this study was to estimate the Operational Expenditure (OPEX) and vessel emissions incurred by hypothetical floating wind projects off the south west coast of the UK. Port requirements were also assessed. The analysis was achieved using the Offshore Renewable Energy (ORE) Catapult's internal Operations and Maintenance (O&M) simulation model, called the Combined Operations and Maintenance, People, Assets and Systems Simulation (COMPASS) tool. The model has been configured to analyse three hypothetical floating offshore wind farms off the south west coast of the UK. For this study, it was assumed that the farms each consist of thirty-three 15MW floating offshore wind turbines on semi-submersible platforms, totalling 495MW per site. The purpose of the report has been to highlight the expected Operational Expenditure (OPEX) and vessel emissions incurred at such a project, as well as giving an indication of port requirements.

To carry out the analyses, a wide variety of input data was used to represent the O&M activities on the floating farms. Some inputs have not been disclosed in this report due to confidentiality, such as specific cost numbers, failure rates and O&M process details. The report provides detail on inspection and repair of floating wind components, for example mooring lines; this is an area of ongoing research (and source of uncertainty in O&M models at present). Three harbours were selected, in turn, for the O&M base of each site, meaning that nine scenarios were simulated in total. A Service Operation Vessel (SOV) was assumed to be the primary vessel used at each farm, although other vessels would be required on an ad-hoc basis.

A vital input for the model is weather time-series data. For this study, weather data was extracted from the ERA5 dataset via the Copernicus website. Assumptions have been made for vessel and personnel specifications, including charter rates, operational weather limits and vessel fuel consumption. Since the COMPASS tool is a stochastic model reliant on component failure rate data, which means that each simulation may produce slightly different results, twenty simulations of each scenario have been carried out (with the average results presented).

The results of the scenario analysis estimate that the floating wind farm located at site 1 (off the south west coast of Wales) would incur £18.7m per year in OPEX (not including some elements seen in other studies, such as seabed leasing, operational insurance and the cost of spare parts) when the O&M base is located at Pembroke Port (its nearest port). This equates to £37.7/kW annual OPEX, which is comparable to other studies analysing demonstration floating wind projects. The same site was estimated to have a time-based availability of 97.2% and an energy-based (or production-based) availability of 96.8%, which corresponds well to bottom-fixed offshore wind farms recorded in ORE Catapult's System Performance, Availability and Reliability Trend Analysis (SPARTA) portfolio review. Other scenarios showed slightly different results, for example site 3 (near the Isles of Scilly) showed the lowest OPEX of the three sites, but only when the O&M base was located at either Newlyn Harbour or Falmouth Harbour (both on the south coast of Cornwall). However, site 3 also showed the lowest availability (e.g. 94.5% time-based availability when Pembroke Port was selected as the O&M base) due to having the harshest weather conditions (particularly significant wave height) thereby reducing

accessibility due to operational limits of vessels. This highlights the need to consider many factors and sensitivities when judging wind farm performance and identifying the optimal O&M logistics strategy.

Vessel usage was also analysed, indicating that a SOV and a survey vessel would be the most heavily utilised vessels at the reference site (regardless of location). Much of the vessels' time would be spent in port if chartered on a long-term basis, highlighting the need for permanent berth/s of suitable size at the O&M base. Of course, the wind farm operator may choose to only charter vessels on an ad-hoc or summer-only basis, which would reduce the need for a permanent berth at the O&M port. The largest vessels that would be required for the projects, albeit less frequently, would be floating Heavy Lift Vessels (HLVs) and Cable Lay Vessels (CLVs).

An analysis of vessel emissions has indicated that an SOV would produce between 1.7kg CO_2e and 2.0kg CO_2e per MWh of energy produced by each site. It should be noted, however, that the propulsion systems of SOVs is an area of ongoing development, with many operators looking for low or zero carbon vessels (e.g. hybrid, full electric, hydrogen or ammonia-powered). Developments in this area may change port requirements, for example, by needing a charge point at the permanent berth at the O&M harbour.

A sensitivity analysis was presented to look at key areas of uncertainty in the modelling approach and strategic decision-making for the project. Changes in the annual charter fee for the long-term lease of a SOV can affect OPEX significantly, highlighting the need for the wind farm operator to consider vessel lease arrangements carefully. Another sensitivity analysis investigated whether two Crew Transfer Vessels (CTVs) would be considered as the primary O&M vessel type for one of the sites close to an O&M port, rather than one SOV. It was found that although the use of CTVs presented an OPEX cost saving, the performance of the project was reduced (i.e. decreased availability and energy production). The strategic decisions surrounding marine logistics can be affected by the monetary value of energy, as any lost energy production is worth more in revenue terms if a higher strike price has been agreed.

There are many areas of uncertainty involved in any kind of O&M modelling. In this study, areas of uncertainty include the O&M activities inputs, vessel charter fees, operational weather conditions, and personnel day rates. Further work at ORE Catapult will aim to address these and improve confidence in the results. Technological developments in the industry may also lead to new types of vessels (e.g. autonomous surface vessels) and O&M techniques (e.g. quicker bolt tightening) being used which are likely to reduce OPEX and improve performance of offshore wind farms. For the specific scenarios presented in this study, further work could look at other ports which may be suitable for locating the O&M base (e.g. Newquay, Port Talbot) or at different vessel charter arrangements (e.g. one SOV with CTVs supporting maintenance during summer campaigns).

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