Assessing the lifetime O&M costs of co-located floating offshore wind and wave farms: a case study in Viana do Castelo, Portugal

Imperadore A., Correia da Fonseca F.X., and Amaral L.

Abstract— **Over recent decades, offshore wind has seen a rapid growth in capacity, number of turbines, turbine size, and required area — a trend that is expected to continue to accelerate. Although less mature and still above grid-parity costs, wave energy remains a promising source of clean renewable energy. Due to its complementarity with offshore wind, co-locating offshore wind and wave energy systems into an offshore hybrid farm may not only reduce generation variability but also take advantage of shared offshore transmission systems, vessels, port infrastructure, and marine area, leveraging the vast and underutilised space between offshore wind turbines. A critical aspect to consider in the development of offshore hybrid farms is the operation and maintenance (O&M) of these assets. In this study, the O&M requirements and costs of wave-floating wind farms are assessed, considering a case study at the Portuguese test-site offshore of Viana do Castelo. Preventive and corrective maintenance plans, as well as port and vessel requirements were identified based on experience and discussions with developers. A weather window assessment based on 30-years of hindcast data was carried out to assess the impacts of weather on vessel chartering strategy and total operation costs. A sensitivity analysis to major sources of uncertainty shows the impacts of changes in the distance to port, reliability assumptions (e.g. failure rates), distribution of failure events, on total O&M costs. Results suggest that co-locating wave and floating wind farms can lead to reductions in total O&M costs due to sharing vessels and electrical assets.**

Keywords— Co-location, hybrid farms, floating offshore wind, wave energy, operation and maintenance (O&M).

This work was supported by European Union's Horizon 2020 research and innovation programme under grant agreement No 101036457, project EU-SCORES.

Imperadore A. is with WavEC Offshore Renewables, Edifício Diogo Cão, Doca de Alcântara Norte, 1350-352, Lisbon, Portugal (e-mail: alessandra.imperadore@wavec.org).

Correia da Fonseca F. X. is with WavEC Offshore Renewables, Edifício Diogo Cão, Doca de Alcântara Norte, 1350-352, Lisbon, Portugal (e-mail: francisco.fonseca@wavec.org).

Amaral L. is with WavEC Offshore Renewables, Edifício Diogo Cão, Doca de Alcântara Norte, 1350-352, Lisbon, Portugal (e-mail: luis.amaral@wavec.org).

I. INTRODUCTION

Aiming to achieve the decarbonisation goals set for 2050, renewable energy sources have been increasingly integrated in the global energy mix. Offshore renewable energies (ORE), in particular, present significant potential for power production, reduced land use, and minimal visual and noise impact. Offshore wind is the leading technology, boasting nearly 70 GW of installed capacity globally as of 2023 [1]. In recent years, other less mature technologies, such as wave energy converters, have been actively tested and developed. This progress is aligned with the European Commission targets for 60 GW of offshore wind, along with 1 GW of ocean energy, by 2030 [2].

As a potential enabler of the anticipated growth in offshore renewable energies over the next decades, the co-location of different renewable generation technologies at the same offshore site has garnered the interest of technology developers, project developers, and policymakers. Several studies have postulated that co-locating wave energy systems with offshore wind in hybrid farms can significantly smooth energy output, leveraging the complementary characteristics of both energy sources [3]. Additionally, co-location may offer significant advantages such as shared use of offshore transmission systems, maritime area, port infrastructure and vessels [3-4]. While S. Astariz et al. have hypothesized additional advantages related to Operation and Maintenance (O&M) in [5-6], there is still a lack of rigorous research quantifying the O&M cost-benefits of co-locating wave and offshore wind systems.

O&M is a major cost-driver in offshore renewable energy projects. In offshore wind, O&M contributes to about 20 to 30% of the Levelised Cost of Energy (LCOE) [7]. In wave energy projects, estimating O&M costs is more difficult due to the lack of long-term operational experience, leading to high uncertainty. However, some studies suggest that as reliability, accessibility, and survivability become critical challenges in wave energy

TABLE I
ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AEP	Annual Energy Production
AHTS	Anchor Handler Tug Support Vessel
CapEX	Capital Expenditures
CLV	Cable Laying Vessel
CTV	Crew Transfer Vessel
FOW	Floating Offshore Wind
HLV	Heavy Lift Vessel
Hs	Significant Wave Height
LCOE	Levelised Cost of Energy
LT	Long-term
MOB	Mobilisation (vessel)
OLC	Operations limit criteria
O&M	Operations and Maintenance
OpEX	Operational Expenditures
ORE	Offshore Renewable Energy
QTY	Quantity
ROV	Remotely Operated Vehicle
T2P	Tow-To-Port
WEC	Wave Energy Converter
WTG	Wind Turbine Generator

devices deployed in harsh wave climates, O&M costs will be equally if not more important [8]. Even though O&M costs in ORE projects are expected to diminish with increased operational experience and economies of scale [9], logistics will be increasingly challenged by greater distances to shore, harsher weather climates, deeper waters, and the need to manage farms with a larger number and size of components. For this reason, it is imperative to investigate whether co-location can indeed streamline logistics and reduce total O&M costs, and, if so, to quantify any benefits.

The present study explores the potential O&M benefits related to the co-location of wave and floating offshore wind farms, with particular focus on shared vessels and electrical infrastructure. This analysis was conducted as part of EU-SCORES [10], an EU-funded project that aims to demonstrate the advantages of co-locating large multi-source offshore renewable energy farms. A case study was carried out for the WindFloat Atlantic floating offshore wind (FOW) pioneering project site, in Viana do Castelo, Portugal [11]. This site is in close proximity to a wave energy site, licensed to CorPower Ocean (CPO), where a 1.2 MW wave energy farm will be tested in the next few years.

The work is structured as follows: Section 2 presents the O&M methodology, and Section 3 details the case study. All relevant results are discussed in Section 4, followed by a sensitivity analysis in Section 5. Finally, the most important outcomes of the work are summarised in Section 6.

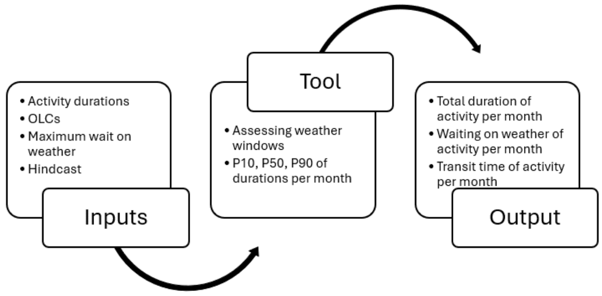

Fig. 1. Flowchart of the simulation approach assessing the statistical durations of offshore operations

II. O&M MODELLING METHODOLOGY

The O&M analysis was conducted using an inhouse time-domain simulation tool, designed to evaluate the lifetime O&M costs of ORE farms. This python-based software is largely built on the open-source DTO+ Logistics & Marine Operations module (LMO), developed within the DTOceanPlus EU-funded project [12], but with improved functionalities and adaptations to accommodate co-located offshore renewable energy farms that can share electrical and vessel infrastructure.

The main functionalities and operating principle of the DTO+ LMO software are described in detail in [13]. In summary, O&M costs are calculated by estimating the durations and downtime associated with a set of operations based on farm design, logistical requirements (e.g. vessel requirements, weather restrictions, offshore work duration) and site metocean data. Two types of maintenance interventions are considered: preventive and corrective, hereinafter collectively referred to as O&M work. Preventive interventions are periodically scheduled and include both inspections and maintenance activities, whereas corrective operations are triggered in response to failure events.

Any offshore maintenance intervention requires planning in advance, with lead times that depend on the type of intervention, vessels required, and types of contracts established with vessel operators. For health and safety (HSE) reasons, offshore operations can only be carried out during sufficiently long periods of good weather. Significant wave height (Hs) is one of the most important metocean parameters that affect the safety and feasibility of an offshore operation. Leveraging the weather window module of the tool, 30 years of hindcast metocean data [14] were used to perform a statistical analysis of potential weather delays for each offshore operation (see Fig. 1). For preventive maintenance interventions, these weather statistics help determine the logistical effort needed to ensure the completion of the O&M work volume. For corrective maintenance interventions, triggered by component failure events, the weather statistics suggest the minimum chartering period considering the uncertainty of a given month and, in some cases, estimate the downtime due to device shutdown that may occur until the components are restored to full functionality. Failure events are generated

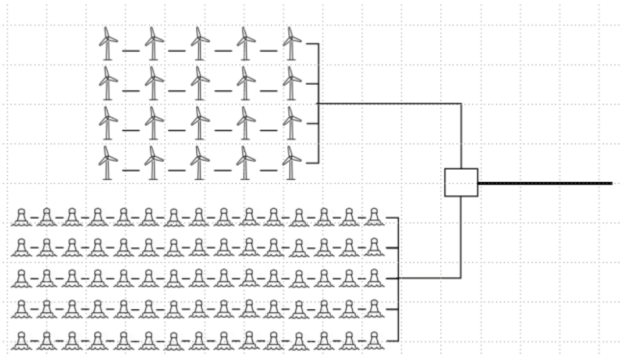

Fig. 2. Schematic representation of the electrical layout for the co-located floating wind and wave energy farms.

based on component reliability and failure distributions, and statistically analysed to quantify their impacts on total costs. Based on the O&M plans, reliability assumptions and the weather window statistical analysis, the direct and indirect O&M costs incurred over the project lifetime can be estimated.

Within the O&M costs of an offshore wind farm, vessels can account for up to 73% of all costs [15]. Different vessel hiring contracts are possible; they are generally defined as short-term when covering chartering periods of weeks to months, and long-term when annually contracted. Short-term chartering offers greater flexibility but is typically more expensive on a daily basis, involves mobilisation lead times and is more exposed to weather-risks. In contrast, annual contracts can ensure full vessel availability, minimal mobilisation delays and can be more cost-effective but only when the work volume justifies it.

Operational data from real offshore wind farms in the United Kingdom (UK), presented in an empirical, anonymised, and aggregated manner, reveal that most farms require frequent visits to site, in some months on a daily basis [16]. In such cases, securing annual contracts for a number of key working vessels, can be a cost-efficient approach compared to short-term daily charter contracts. This is especially true for Crew Transfer Vessels (CTVs), which can be used to handle the majority of preventive and minor corrective maintenance interventions. The optimal number of CTVs to be secured by annual contracts (hereinafter referred to as LT CTVs) can be determined by comparing a given O&M work volume in a year, measured in net workdays, with the expected number of workable days in a year (i.e., days with good weather). Subsequently, the total chartering costs of various combinations of annual and short-term contracts can be analysed for different numbers of LT CTVs. The need for short-term vessel contracts is based on the chartering period, estimated according to the remaining O&M work volume not covered by the LT CTVs. Based on the remaining net workdays, the statistical analysis of the metocean suggests the minimum chartering period, expressed in months, to ensure the completion of the work. For high remaining workloads, the number of CTVs to be chartered short-term was calculated by prioritising solutions with fewer vessels but longer charter durations over solutions with more vessels for shorter periods. While there may be some cost benefits to chartering more CTVs during brief periods of significantly better weather, the adopted approach is considered simple, conservative, and appropriate for an initial analysis. As a simplification, the minimum charter length for short-term CTVs was also set at one month. Finally, the optimal number of LT CTVs is the one that minimises total vessel expenditures, which may not necessarily eliminate the need for additional short-term chartering of CTVs, as these can be a cost-effective way to mitigate peak workloads. Once the optimal combination of LT CTVs and ST CTVs is determined, it can be fed into the O&M modelling tool to assess lifetime O&M costs.

III. CASE STUDY

A case study was conducted on the co-location of a wave energy farm with a floating offshore wind farm off the coast of Viana do Castelo, Portugal. This site, close to the WindFloat Atlantic 25 MW pre-commercial FOW project [11], is located within one of the key areas designated for the upcoming floating offshore wind auctions in Portugal [17]. Due to its relevance to the wave and floating offshore wind sector, this offshore site was extensively studied and was thus selected for the case study.

In the present study, the co-location of a 300 MW FOW farm and a 30 MW wave energy farm was considered (see Table II). It is assumed that both farms share the electrical transmission infrastructure, as illustrated in the electrical layout in Fig. 2. The average distance and transit duration between the offshore wind turbines are estimated based on pre-defined inter-turbine spacing within each farm. The same is done for the wave energy units.

Despite the significant differences in logistical requirements between the two farms, CTVs facilitate nearly all offshore operations in wave energy farms, and

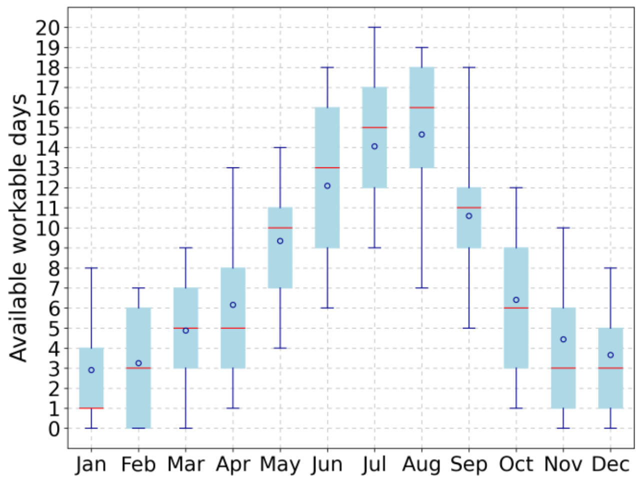

Fig. 3. Quantile plots of the available workable days per month at the offshore site in Viana do Castelo, considering an operational threshold of Hs = 1.5m, based on 30 years of hindcast metocean data. The red bar and small blue circles represent the median and mean, respectively. The rectangle represents the P25 and P75 boundaries, while the P10 and P90 percentiles are represented as blue whiskers.

most inspections and minor repair interventions in floating wind (about 75-77% of failure events require minor interventions that can be handled by CTVs) [15], [18]. For both farms, the environmental threshold for carrying out O&M interventions on CTVs was limited to 1.5 m Hs according to internal offshore experience [15]. In some cases, the assignment of multiple CTVs chartered in parallel is considered to carry out the O&M work while reducing the total campaign duration and exposure to weather delays.

In Fig. 3, the expected number of workable days per month offshore of Viana do Castelo is depicted as interquartile plots, using the median as a reference point. The P10, P25, P75 and P90 percentiles are included to illustrate the annual variability and dispersion of the data. As expected, workable days are predominantly concentrated in the summer months, when the majority of the O&M work volume is scheduled. Nevertheless, significant inter-annual variability during those months suggest that the risk of weather delays should not be overlooked in the planning process. It must be noted that the hydrodynamic interactions and sheltering effects between wave and floating wind devices are not considered in this study.

While relevant, the benefits in Capital Expenditures (CapEx) from sharing infrastructure are not considered as the study focuses exclusively on the operational stage of the project.

Even though the downtime associated with failure events and O&M work is not examined in the present analysis, it is assumed that every failure triggers an immediate corrective response, scheduled for as soon as the vessel can be mobilised and weather conditions permit. While it is acknowledged that for some components and lower-risk failure modes, corrective intervention can be deferred to months with better weather and/or grouped with other maintenance interventions opportunistically, this approach remains conservative.

A. FOW Farm

A 300 MW floating wind farm was considered, comprised of twenty 15 MW wind turbine generators (WTGs). An average inter-turbine spacing of seven rotor diameters (7D), was assumed. O&M requirements and data were gathered from discussions with developers and data available in the literature [18].

TABLE II
CO-LOCATED FARMS INPUTS

Input	Value
Coordinates	(41.0, -9.0)
Project lifetime	30 years
Distance to port	25 km
Number of export cable	1
Length of export cable	17 km
Total installed capacity	330 MW
FOW farm capacity	300 MW
Wind turbine rated power	15 MW
Wave farm capacity	30 MW
Wave converter rated power	0.4 MW

TABLE III
300 MW FOW FARM LOGISTICS

Term	Qty	Type of contract	Unit charter costs
CTV	3	Annual contract	573,050 €/year
CTV	1	Daily hired + mob	4,000 €/day [13]
HLV	1	Daily hired + mob	300,000 €/day
CLV	1	Daily hired + mob	177,000 €/day [19]
Survey vessel	1	Daily hired + mob	4,200 €/day [13]
AHTS	1	Daily hired + mob	35,000 €/day [19]

To calculate total mobilisation costs, three days of mobilisation time are considered, multiplied by the daily rate. Fuels costs not included.

Each WTG is estimated to require 54 hours of net preventive work for an in-depth inspection to all major components. Comprehensive inspection campaigns are planned yearly to cover 50% of the devices, requiring 70 net workdays. Additionally, a light inspection is scheduled every year to 100% of the turbines in the farm and spanning over 5 net workdays (not considering weather delays) for a 20-turbine farm. Visual surveys to umbilical and export cables are considered every two years. Inspections to mooring lines and umbilical cables are carried out with ROVs, while inspections to (buried) export cables can be done from the surface using a survey vessel equipped with specialised instruments such as multibeam sonars (see Table III).

Corrective maintenance, triggered by failure events, is logistically more challenging as requirements will depend on the level of criticality of the failure. Failure rates were gathered from [18] with the assumption of associated lead time for procurement, delaying the offshore intervention.

In general, for minor and medium repairs, which do not require large vessels nor heavy crane work and are the most frequent types of failures, can be serviced with CTVs. Major component replacements, namely to blades, gearboxes and generators, will require a floating heavy lift vessel (HLV). While having been the only viable option in the recent past to carry out major component replacements in large floating wind turbines, tow-to-port (T2P) maintenance was not considered in this study as it is not seen to be a scalable solution for large commercial-scale floating wind farms [20]. Alternative solutions such as using a smaller construction vessel and climbing crane technologies, while relevant and with very high cost-reduction potential, were not considered due to their lower maturity [21-23]. Mooring line replacements are assigned to an anchor handling tug support vessel (AHTS) and one support tug. For export or umbilical cable failure, a cable laying vessel (CLV) is deemed necessary.

For this farm size, combining both preventive and corrective maintenance, an average of 164 site visits per

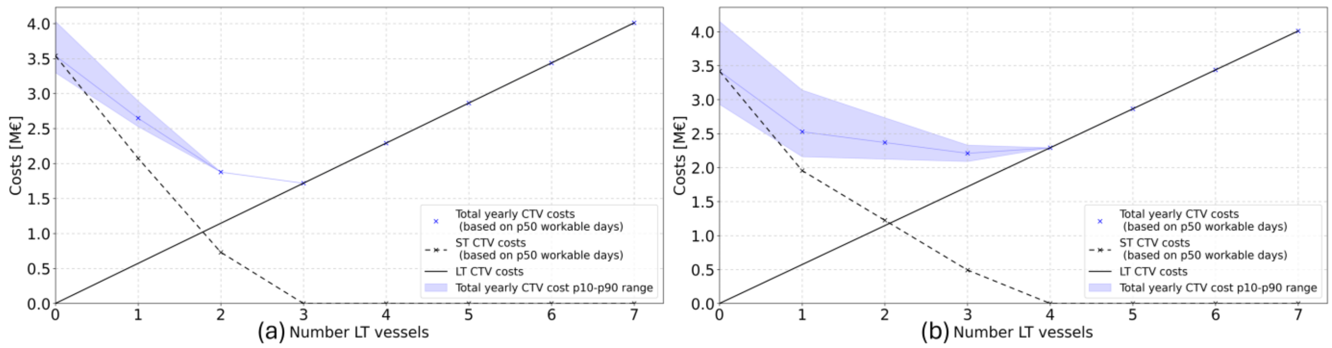

Fig. 4. Total yearly hiring cost of CTVs (fuel not included) for a 300 MW FOW farm (a) and a 30 MW wave energy farm (b).

year is expected (8.2 visits per device per year on average), 95% of which require CTVs. It was observed that 80% of all site visits are due to corrective maintenance.

The overall logistic requirements are summarised in Table III. The optimal number of CTVs to be chartered in the long-term was determined as the one that minimises total yearly CTVs costs. Fig. 4a presents the cost results based on the P10, P50 and P90 workable days in a year at the offshore site, for different numbers of CTVs secured through long-term contracts. As expected, as the number of annually contracted increases, the associated costs (LT CTV costs) increase linearly and the requirement for additional short-term chartering decreases (and so do the associated costs, shown in the dashed line). The total CTV hiring costs, shown by the blue line, decrease as the number of LT CTVs increases, reaching a minimum with three LT CTVs. Additionally, the P10-P90 interval, which captures 80% of all observations, is represented in light blue. Given that short-term CTV chartering costs are particularly sensitive to weather uncertainty, the blue area shrinks with an increasing number of LT CTVs, reflecting the reduced contribution of short-term vessels to total costs. Moreover, it can be observed that the blue area converges to zero before converging with the LT curve, which can be explained by the fact that most of the O&M workload of short-term vessels is concentrated in the winter period where the statistical dispersion is lower (see Fig. 3).

As previously mentioned, the CTVs hiring cost assessment suggests that for this farm size, wave climate, O&M plan, and location, the cost-optimal number of LT CTVs is three. Above this number, the cost of an additional CTV annual contract would not be covered by the cost-savings in short-term vessel hiring. Considering the median number of workable days from the weather assessment, this solution corresponds to a vessel utilisation of approximately 75% in the summer and 78% in the winter due to the high failure rates (around 130 visits per year triggered by failure events). Notably, CTVs may also be required as support during major component replacements serviced by larger vessels such as HLVs. Nevertheless, for the purpose of this study this additional workload was considered negligible.

TABLE IV
LIFETIME RESULTS FOR THE FLOATING OFFSHORE WIND FARM

Term	Value	Unit
Lifetime O&M costs	2.349	M€/MW
Yearly O&M costs	78.3	k€/MW/year
Lifetime OpEX costs[a]	3.100	M€/MW

[a]Considering other OpEX costs such as insurance, ports and onshore logistics from [19].

After having identified the cost-optimal number of CTV vessels to be hired on an annual basis, the O&M tool was used to assess the lifetime O&M costs, resulting in 704.7 M€, which corresponds to 78.3 k€/MW/year (see Table IV). Direct cost comparisons with other sources are challenging due to an absence of standardized cost structures. However, reference [19] was used as it provides a breakdown of different costs, per MW per year, of O&M for a 450 MW floating offshore wind. All costs are related to the year 2021 and were converted to euro considering the 2021 conversion rate [24], yielding an average of 83.4 k€/MW/year. For comparison purposes, cost elements such as insurance, port, onshore logistics and support staff, training and operations control centre costs were sourced from reference [19] and added to the modelled costs (about 25k€/MW in 2024 Euros), resulting in a yearly OpEX of 103.3 k€/MW/year. This value is approximately 24% higher than ORE Catapult's value in [19], which can be explained primarily by the different set of assumptions, including factors such as wave climate considered, distance to port and adopted maintenance strategy (the reference study considers both T2P and in-situ maintenance for major repairs).

B. *Wave energy farm*

TABLE V
30 MW WAVE FARM LOGISTICS

Term	Qty	Type of contract	Unit charter costs
CTV	3	Annual contract	573,050 €/year
CTV	1	Daily hired + mob	4,000 €/day [13]
Work vessel	1	Daily hired + mob	10,000 €/day [13]
CLV	1	Daily hired + mob	177,000 €/day [19]
Survey vessel	1	Daily hired + mob	4,200 €/day [13]

To calculate total mobilisation costs, three days of mobilisation time are considered, multiplied by the daily rate. Fuels costs not included.

TABLE VI
LIFETIME RESULTS FOR THE WAVE FARM

Term	Value	Unit
Lifetime O&M costs	8.583	M€/MW
Yearly O&M costs	286	k€/MW/year
Lifetime OpEX costs[a]	9.03	M€/MW

[a]Estimated considering expenditures associated with ports, onshore logistics and insurance.

A 30-MW wave energy farm was considered, comprised of seventy-five 400 kW devices. CorPower Ocean's Wave Energy Converter (WEC) concept was considered as a reference. O&M requirements and assumptions were gathered from discussions with the developer and complemented by peer-reviewed sources when applicable.

For the WEC farm, scheduled maintenance activities include both on-site and at-port work. Annual on-site inspections for each device are considered and estimated to take about 24 hours in total per device per year. Inspections to the dynamic array cables and export cable are planned for every two years, which is in line with offshore wind industry best practices. Subsea visual inspections, which also include inspections to the hull, mooring lines and anchors, are planned with the aid of remotely operated vehicles (ROV) to improve safety and reduce costs. Additionally, comprehensive maintenance is conducted at port every five years, during which major component replacements and refurbishment interventions take place. Corrective interventions are reduced in number, and justified by the periodic and intensive port maintenance factored into the planning. Failure rates were gathered from discussions with the developers with an associated lead time for the procurement that delays the offshore operation.

Considering preventive and corrective maintenance (based on component failure rates provided), an average of 128 visits to site per year can be expected, which corresponds to approximately 4.3 visits per device per year.

For most on-site O&M work (86%), CTVs are suitable. It is considered that the selected CTVs are capable of launching and operating small inspection class ROVs for subsea inspection to umbilical cables, hull and moorings.

Fig. 5. Example of suitable multi-purpose work vessel for O&M in the wave energy farm (From: [25]).

Similarly to the installation phase, a multi-purpose work vessel with a crane and sufficient bollard pull capabilities, is considered for carrying out the disconnection procedures and towing of the device to port (see Fig. 5). Additionally, a CTV will serve as an escort tug to assist in towing the device, providing extra stability and safety by tensioning the towline and ensuring a controlled and secure towing operation. In the event of a mooring system failure, a similar fleet of vessels would be used. Anchor failures would require a HLV for removal and reinstallation, however this failure mode is considered to be extremely unlikely and not accounted for. Similarly to offshore wind farms, export cable inspections are conducted by a survey vessel. Failures to the export or umbilical cables are to be handled by a CLV. The overall logistical requirements and inputs are summarised in Table V.

Considering the list of CTV-relevant O&M operations and the expected number of available workable days at the site, the optimal number of CTVs to be chartered in the long-term for the wave energy farm was determined based on the CTVs hiring cost assessment in Fig. 4b. Results suggest that the cost-optimal CTV solution consists of hiring three CTVs under annual contracts and all remaining vessels chartered sporadically every now and then when the work volume justifies it. Despite the significantly higher number of wave energy converters, compared to turbines in the FOW farm, each WEC requires fewer overall maintenance hours, coincidently leading to a similar result as in the floating offshore wind farm. These three LT CTVs dedicated to the wave farm have a utilisation factor of 100% during the summer months when preventive maintenance work is planned. The utilisation factor is calculated as the ratio between the number of workdays and the expected (P50) number of good weather days (workable) in the period. The utilisation factor drops below 10% in the winter due to the low number of corrective interventions. This is further illustrated by the P10-P90 interval (area in blue), which is wider than in Fig. 4a. This is due to the assumptions for which 98% of the O&M work at the wave farm is preventive, and therefore planned for the summer months when the weather is better on average but subjected to higher inter-annual variability (see Fig. 3).

After determining the cost-optimal number of

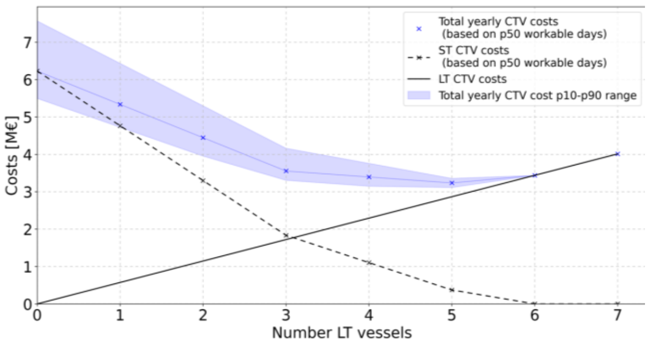

Fig. 6. Total yearly hiring CTVs cost for co-located farms.

annually-chartered CTVs to be considered in the wave energy farm, O&M simulations were conducted, and the associated costs were estimated. The modelling results indicate a total lifetime O&M cost of 257.5 M€, which corresponds to 8.583 M€/MW and 0.286 M€/MW/year (see Table VI). Based on internal experience and discussions with the developer, about 450 k€ of yearly costs related to port and insurance were estimated. When combined with the O&M costs from the simulations, this resulted in a total lifetime OpEX of 270.8 M€.

Due to the early commercial stage of the technology, there are limited studies available in the literature to benchmark the results of the O&M modelling. Costs were compared to the Gray et al. study [8] which analyses a wave energy farm, comprised of P2 Pelamis devices. The study reported O&M costs of approximately 0.160 M€/MW/year in O&M costs (originally in pounds, converted to Euros using the 2017 conversion rate [24] and subsequently adjusted to 2024 values). This significant discrepancy in costs may be attributed to the different underlying assumptions, deployment sites and associated wave climates, as well as overall maintenance strategies considered in each study. Gray et al. [8] assumes only onshore maintenance for the device, with preventive maintenance limited to a 7-day annual general inspection and extensive maintenance every 10 years. In contrast, the present paper considers each device undergoing approximately four visits per year for preventive maintenance, along with extensive port maintenance every 5 years – twice as frequently as considered in [8]. Regarding the corrective interventions, Gray et al. estimated about 14 failures per device per year [26], while the present study estimates approximately 3 visits per year to the entire farm due to component failure, a slightly lower estimate. This deviation will be further investigated in the sensitivity analysis.

C. *Co-located FOW and wave energy farms*

Having simulated the O&M phase of the floating wind and wave energy projects, individually, the case where both farms are co-located was studied. The assessment set out to investigate the potential opportunities for vessel sharing, and then quantify the benefits due to sharing electrical infrastructure.

Given that CTV vessels facilitate a very large portion of the total number of O&M interventions in a year for both individual farms (around 95% in both farms), a new analysis to the optimal number of CTVs to be secured under annual contracts for the co-located scenario was conducted. When deployed individually, both floating wind and wave energy farms seem to require three CTVs each, secured under long-term contracts and sporadically supplemented by short-term charters.

TABLE VII
WORKLOAD COMPARISON WAVE-FLOATING WIND

Parameter	FOW Farm	Wave Farm
Workload (days/MW)	0.7	7.3
Workload (days/unit)	10.7	2.9

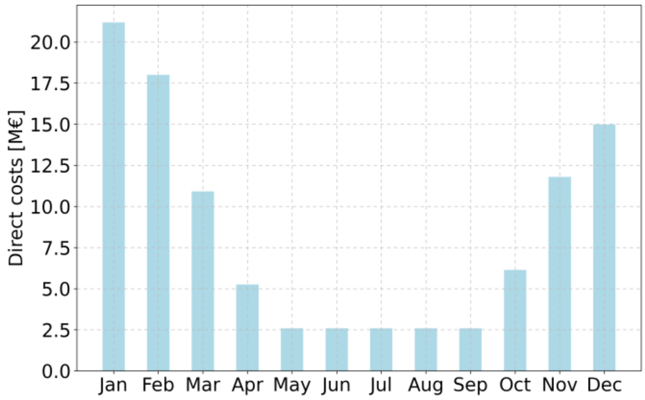

Fig. 7. Monthly direct costs of export cable repair.

However, the results of the analysis to the co-located farms suggest that the new cost-optimal number is five CTVs chartered annually (see Fig. 6). This reduction in total number of vessels is due to the complementary demand for O&M work between farms. As illustrated in Table VII, the wave farm requires a substantial logistical effort per unit of power installed, necessitating a high number of workdays. By sharing vessels with the wind farm, more vessels can be allocated to the O&M work, reducing total durations and exposure to weather delays. Additionally, the wind farm is expected to require significant offshore intervention due to corrective maintenance, potentially more concentrated in winter, due to stronger winds [27]. Because of the low utilisation of the CTVs during the winter months in the wave farm, these vessels can be used to service the wind farm, thus enhancing overall service reliability.

In respect to sharing the electrical infrastructure, the main benefits originate from managing and maintaining one export cable instead of two. This results in halved inspection costs and repair costs, even though costs related to the export cable repair will vary depending on the timing of the failure. Fig. 7 presents the monthly direct costs based on the P50 weather assessment for one export cable repair. For the lifetime cost assessment, a failure rate of 0.003/km/year was considered [28].

Having simulated the entire O&M phase of the co-

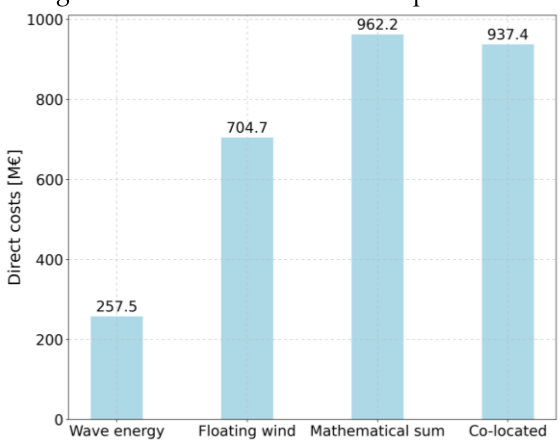

Fig. 8. Average O&M direct costs comparison.

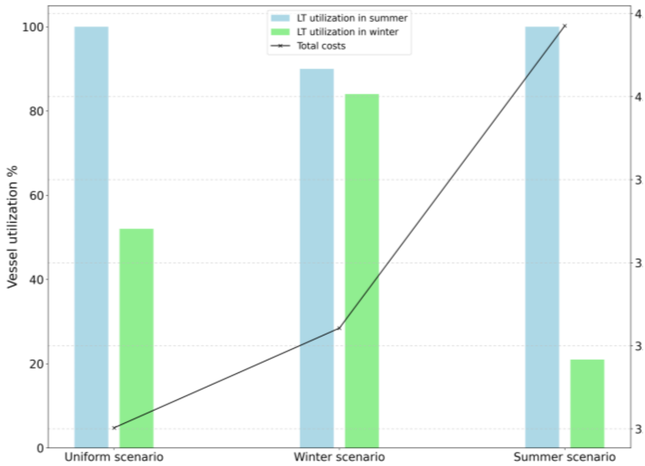

Fig. 9. Long-term vessels utilisation and total CTVs hiring costs for different scenario of failure distributions.

located farms, the lifetime O&M costs of the hybrid project was over 937.4 M€, which corresponds to 94.7 k€/MW/year (see Table VIII). In Fig. 8, the total O&M costs for the co-located scenario are compared against the total costs of each individual farm. It can be observed that even though the O&M costs of the co-located farm are 33% higher than for the floating wind farm alone, these costs are 2.58 % lower than the mathematical sum of the lifetime O&M cost of each individual farms (962 M€).

Results show that sharing LT CTVs reduces total lifetime costs by approximately 1.0%, whereas sharing the electrical infrastructure is responsible for the 1.58% reduction in lifetime O&M costs due to fewer required inspections and corrective interventions. Other OpEX elements such as insurance, operational control centre, and port logistics were not accounted for in this comparison, though it can be argued that additional cost savings may be realized in these areas as well.

IV. SENSITIVITY ANALYSES

A sensitivity analysis was carried out to three main assumptions to evaluate how changes in inputs and variables could impact the overall results and robustness of the assessment.

A. *Failure distribution over the year*

O&M studies are generally very sensitive to the failure

TABLE VIII
LIFETIME RESULTS FOR CO-LOCATED WIND AND WAVE FARMS

Term	Value	Unit
Lifetime O&M costs	2.841	M€/MW
Yearly O&M costs	0.095	M€/MW/year

modes, frequencies, and distributions considered, which are also subject to a high degree of uncertainty due to limited data. While there are some evidences that wind turbine failures events are correlated with periods of high wind speeds (namely during wintertime), there is limited data on this effect [27].

The first preliminary analysis to the cost-optimal number of annually chartered CTVs in a co-located offshore wind and wave energy farm was repeated for three different failure distribution scenarios: (1) Uniform distribution Scenario, where failure events are assumed to have equal probabilities of occurrence throughout the year, (2) Summer (concentrated) Scenario, where 80% of the failure events (and consequently unplanned maintenance) are assumed to occur during the summer, coinciding with most of the preventive work volume, and (3) Winter (concentrated) Scenario, where 80% of the failure events occur during the winter, when accessibility is lower.

Despite the inevitable increase in lifetime O&M costs, the results confirm that the cost-optimal number of CTVs to secure under annual contracts remains five vessels, for all scenarios. The annually averaged utilisation factor of the LT CTVs is shown in Fig. 9. It can be observed that for all cases, during the summer period, the LT CTVs will be working near full capacity, with sporadic need of additional short-term chartering of vessels. In contrast, the corrective O&M work during the winter months is always fully covered by the long-term vessels, leaving some margin for any additional work that may arise.

Interestingly, the uniform scenario results in the lowest O&M costs, while the highest costs are observed in the third case, where failures are concentrated in the summer, despite the significantly better accessibility. This is due to the fact that the LT CTVs are already near full capacity during the summer months when most of the preventive maintenance work is scheduled. Nevertheless, it is

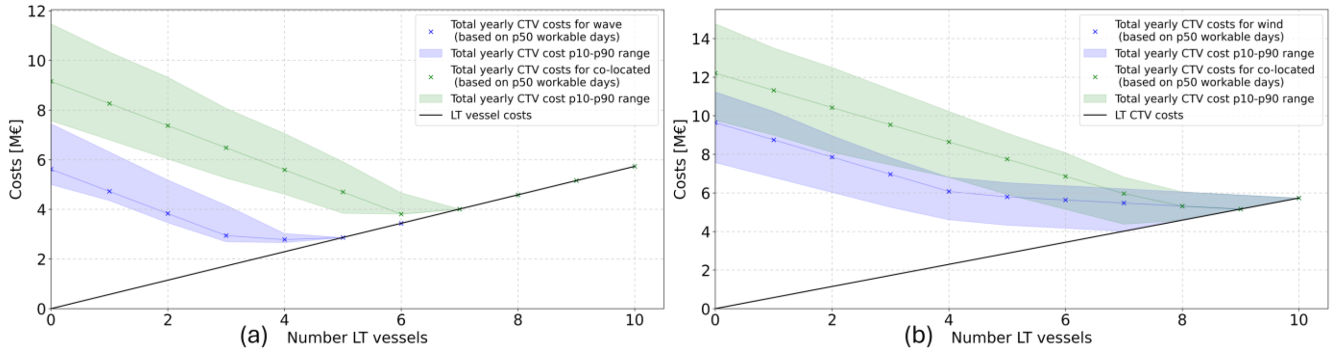

Fig. 10. Total yearly hiring cost of CTVs in case of an increased failure rate: (a) Increased failure rate of the wave farm and its impact on co-located farms, (b) increased failure rate of the offshore wind farm and its impact on co-located farms.

important to note that this study does not account for potential downtime associated to the corrective interventions, which could significantly increase (indirect) costs during the winter periods and potentially alter the conclusions of this analysis.

B. Failure rate assumptions

A second sensitivity analysis examines the corrective workload, taking into account different failure rates reported by different sources [16], [26] for the two farms.

For the wave energy farm, using the overall failure rate for the Pelamis P2 device reported in [26], an annual value of 1.87 failures per device was estimated. This corresponds to approximately 140 failures per year for the 30 MW farm considered in this study, which is about 50 times higher than the failure rate assumed in the initial analysis. Despite difference between the two systems, and assuming that each failure triggers one site visit with a CTV, the number of visits was scaled linearly to match the 140 failure events. The results for the optimal number of LT CTVs are in Fig. 10a, indicating an increase from three to four vessels according to the P50 assessment. This impact is also reflected in the co-located farm results, where the optimal number now stands at six, for which the benefit of co-location remains present (the wind farm alone requires three CTVs). In terms of overall costs, scaling the failure rates to reach the number of visits suggested in [26] results in almost doubling the O&M costs to 437 M€.

The same analysis was conducted for the wind farm, considering the six transfers per month per turbine observed in 2020 as indicated in reference [16]. Assuming three technicians for each transfer, two visits per turbine per month are expected, which is 3.2 times higher than previously assumed. As with the previous case, Fig. 10b presents the CTVs hiring costs assessment. The optimal number of CTVs increases significantly for the wind farm, whereas for the co-located farms, the increase is not proportional, indicating that the benefit from sharing vessels remains.

C. Distance to port

Finally, a sensitivity analysis was caried out varying site to port distances. A higher distance leads to increased durations and exposure to weather delays, requiring additional logistical effort.

The analysis was repeated for a range of port-to-site distances between 10 and 50 km. The maximum port-to-site distance was set at 50 km, as this is generally considered the limit for CTVs [29]. Beyond this distance, larger vessels like Service Operation Vessels (SOVs), which can remain on-site overnight, can be a preferred option to service such farms [30]. Although more expensive, these vessels offer the advantage of operating in harsher weather conditions and higher significant wave heights (Hs).

Although higher fuel costs were incurred due to longer transit durations, the weather window analysis indicated that the same workload could be completed within the same timeframes. As a result, there was no impact on the optimal number of CTVs to be secured under annual contract for both farms, and ultimately, the conclusions on the O&M cost-benefits of co-location remain unchanged.

V. CONCLUSIONS

The present paper analyses the potential O&M benefits of co-locating a wave energy farm with a floating offshore wind farm. Having identified the O&M requirements of each farm, the study explored the synergies derived from sharing annually-contracted vessels and a common offshore electrical system.

The results suggest that CTVs are required for approximately 95% of site visits for both farms. Due to their extensive use and year-round demand, securing vessels under annual contracts proves beneficial, ensuring availability and reliable service. The optimal number of CTVs for each farm was assessed, revealing that co-locating the farms reduces the number of long-term vessels needed for overall O&M work, compared to the combined requirements of the two separate farms. This trend remained consistent in both the base case, where the wave energy farm had a limited corrective workload, and in the sensitivity analysis, in which considered a significantly higher failure rates.

Integrating a wave energy farm into an existing floating wind project will inevitably increase total O&M expenditures, both in terms of cost per MW installed per year and in total lifetime costs. However, compared to operating two independent farms, co-location can unlock cost-savings of approximately 2.58% in total lifetime O&M expenditures. While vessel sharing accounts for the majority of this reduction, additional savings are achieved through the shared electrical infrastructure, as managing a single system is less costly than handling two separate assets. Finally, potential cost reductions in other OpEX areas—such as insurance, operational control centre, training, and port logistics—were not analysed in detail but are likely to provide further savings in a well-articulated co-location scenario.

The present findings highlight the importance of further analysis on co-located offshore wind and wave farms. Future research should include an examination of revenue losses due to downtime associated with the O&M plan, which was not considered in the present study. Additionally, given the expected growth trends in offshore renewable energy, future work should analyse farms located farther from port, serviced by larger vessels capable of overnight stays, and explore the potential benefits of their shared vessel utilisation.

ACKNOWLEDGEMENT

This work has been supported by European Union's Horizon 2020 research and innovation programme under grant agreement No 101036457, project EU-SCORES.

REFERENCES

[1] G. Herzig, "Global Offshore Wind Report," Apr. 2024. [Online] Available: WFO-Report-2024Q1.pdf (wfo-global.org) (accessed on 5 June 2024)

[2] European Commission, "Communication from the Commission to the European Parliament, The Council, The European economic and social Committee and the Committee of the regions Delivering on the EU offshore renewable energy ambitions", COM(2023) 668 final.

[3] C. Pérez-Collazo, S. Astariz, J. Abanades, D. Greaves, G. Iglesias, "Co-located wave and offshore wind farms: a preliminary case study of an hybrid array," Internation Conference in Coastal Engineering, vol. 34, June 2014. DOI: http://dx.doi.org/10.9753/icce.v34.structures.33, [Online].

[4] M. H. Qais, H. M. Hasanien, S. Alghuwainem, "Output power smoothing of wind power plants using self-tuned controlled SMES units," Electric Power Systems, Research, vol. 178, 106056, ISSN 0378-7796, Jan. 2020. DOI: https://doi.org/10.1016/j.epsr.2019.106056, [Online].

[5] S. Astariz, C. Pérez-Collazo, J. Abanades, G. Iglesias, "Towards the optimal design of a co-located wind-wave farm," Energy, vol. 84, pp 15-24, ISSN 0360-5442, May 2015. DOI: https://doi.org/10.1016/j.energy.2015.01.114, [Online]

[6] S. Astariz, C. Pérez-Collazo, J. Abanades, G. Iglesias, "Co-located wind-wave farm synergies (Operation & Maintenance): A case study," Energy Conversion and Management, vol. 91, pp 63-75, ISSN 0196-8904, Feb. 2015. DOI: https://doi.org/10.1016/j.enconman.2014.11.060, [Online].

[7] A. Gray, "What are operations and maintenance simulation tools? An explanation of O&M models in the offshore renewable energy sector", Aug. 2020. [Online] Available: What are Operations and Maintenance Simulation Tools? (catapult.org.uk) (accessed on 5 May 2024)

[8] A. Gray, B. Dickens, T. Bruce, I. Ashton, L. Johanning, "Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters," Ocean Engineering, vol. 141, pp 493-511, ISSN 0029-8018, Sep. 2017. DOI: https://doi.org/10.1016/j.oceaneng.2017.06.043, [Online].

[9] Offshore Wind Innovation Hub, "Operations & Maintenance: Cost drivers," INDUSTRY INSIGHTS SERIES. [Online] Available:https://offshorewindinnovationhub.com/wp-content/uploads/2020/08/OWIH-Report_OM-Cost_Drivers.pdf (accessed on 11 July 2024)

[10] European Commission, "European Scalable Complementary Offshore Renewable Energy Sources." [Online] Available: https://doi.org/10.3030/101036457 (accessed on 11 July 2024)

[11] WindFloat Atlantic, "World's first semi-submersible floating offshore wind farm," [Online] Available: Windfloat Atlantic | Offshore wind energy (windfloat-atlantic.com) (accessed on 27 June 2024)

[12] European Commission, "Advanced Design Tools for Ocean Energy System Innovation, Development and Deployment." [Online] Available: https://doi.org/10.3030/785921 (accessed on 11 July 2024)

[13] F. X. Correia da Fonseca, L. Amaral, P. Chainho, "A Decision Support Tool for Long-Term Planning of Marine Operations in Ocean Energy Projects,", Journal of Marine Science and Engineering, vol. 9, pp 810, July 2021. DOI: http://dx.doi.org/10.3390/jmse9080810, [Online]

[14] Matías Alday G., and George Lavidas, (2024), The ECHOWAVE Hindcast: A 30-years high resolution database for wave energy applications in North Atlantic European waters, Renewable Energy, Elsevier.

[15] Y. Dalgic, I. Dinwoodie, I. Lazakis, D. McMillan, M. Revie, "Optimum CTV Fleet Selection for Offshore Wind Farm O&M Activities,", European Safety and Reliability Conference ESREL, Sep. 2014. DOI: http://dx.doi.org/10.1201/b17399-164, [Online]

[16] ORE Catapult, "System Performance, Availability and Reliability Trend Analysis – SPARTA: 2020/2021 Portfolio Review". [Online] Available: SPARTA-Review-2021-Final.pdf (catapult.org.uk) (accessed on 14 June 2024)

[17] S. Goncalves, "Portugal launches initial phase of offshore wind auction,", Reuters, Nov. 2023. [Online] Available: Portugal launches initial phase of offshore wind auction | Reuters (accessed on 27 June 2024)

[18] H. Li, W. Peng, C.-G. Huang, C. Guedes Soares, "Failure Rate Assessment for Onshore and Floating Offshore Wind Turbines," Journal of Marine Science and Engineering, 10(12):1965, Dec. 2022. DOI: https://doi.org/10.3390/jmse10121965, [Online]

[19] BVG Associates, ORE Catapult, The Crown Estate, "The guide to a Floating Offshore Wind," Mar 2023. [Online] Available: Guide to a floating offshore wind farm | An informative resource for floating offshore wind (guidetofloatingoffshorewind.com) (accessed on 14 June 2024)

[20] The Carbon Trust, ABL Group, WavEC Offshore Renewables, Leask Marine, "Phase III summary report, Floating Wind Joint Industry Project," The Carbone Trust, 2021

[21] MAMMOET, "Mammoet heralds new era for wind turbine assembly and maintenance." [Online] Available: https://www.mammoet.com/news/mammoet-heralds-new-era-for-wind-turbine-assembly-and-maintenance/ (accessed on 10 July 2024)

[22] WINDSPIDER, "Windspider Crane System Ready for Next Generation of 20MW+ Wind Turbines." [Online] Available: https://windspider.com/ (accessed on 10 July 2024)

[23] SENSEwind, "Installing and servicing turbines higher.. deeper.. safer.. cheaper.. anywhere."[Online] Available: https://sensewind.com/ (accessed on July 2024)

[24] Exchange Rates UK, "Euro to British Pound Spot Exchange Rates" [Online], Available: https://www.exchangerates.org.uk/EUR-GBP-spot-exchange-rates-history-2017.html (accessed on July 2024)

[25] Nsea, "N-Sea strengthens offshore services with Multipurpose Support Vessel Geosea," Apr 2022. [Online] Available: https://www.n-sea.com/news-and-media/n-sea-strenghthens-offshore-subsea-services-with-multipurpose-support-vessel-geosea/ (accessed on 10 July 2024)

[26] A. Gray, "Modelling Operations and Maintenance Strategies for Wave Energy Arrays", June 2017. DOI: http://hdl.handle.net/1842/28845, [Online]

[27] J. Carroll, A. McDonald, D. McMillan, "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines," Wind Energy, vol. 9, pp 1107-1119, June 2016. DOI: https://doi.org/10.1002/we.1887,[Online]

[28] J. Warnock, D. McMillan, J. Pilgrim, S. Shenton, "Failure Rates of Offshore Wind Transmission Systems," Energies, May 2019. DOI: https://doi.org/10.3390/en12142682, [Online]

[29] E. Haun, "Building a New Fleet: CTVs For U.S. Offshore Wind," Marine New, Dec. 2021. [Online] Available: Building a New Fleet: CTVs for U.S. Offshore Wind (maritimemagazines.com) (accessed on 27 June 2024)

[30] Offshore Wind Innovation Hub, "Floating Wind: Cost modelling of major repair strategies," INDUSTRY INSIGHTS SERIES. [Online] Available: https://offshorewindinnovationhub.com/wp-content/uploads/2020/09/OWIH-Report-Floating_Wind_OM.pdf (accessed on 11 July 2024)