FLOATING WIND JOINT INDUSTRY PROGRAMME

Onsite Major Component Replacement

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ONSITE MAJOR COMPONENT REPLACEMENT (OMCR)

Introduction

The Onsite Major Component Replacement (OMCR) project was delivered by Fazer-Nash Consultancy in collaboration with Generating Better and FloWave on behalf of the Floating Wind Joint Industry Programme (Floating Wind JIP).

Major component replacements are a significant contributor to both the levelized cost of energy (LCOE) of floating offshore wind (FOW) and uncertainty in project development. Two main solutions are currently considered for the major replacements in floating offshore wind farms: Tow-To-Shore (TTS) and Onsite MCR (OMCR). Previous studies conducted as part of the Floating Wind JIP have investigated both solutions, including tow to port maintenance, heavy lift offshore maintenance (HLM), and major component exchange with self-hoisting cranes (SHC), and demonstrated that OMCR can provide a lower-cost solution then TTS for commercial scale FOW farms. However, low technology readiness levels (TRL) and the lack of a clear concept-to-deployment framework are key barriers to the confident adoption of OMCR solutions. This is compounded by varying or unclear requirements for different solutions and turbine-foundation configurations.

This project is intended as the initial step in supporting that process. It builds on existing projects to evaluate OMCR concepts currently in development and develop a tank test specification that could be executed in subsequent phases to build further confidence in modelling results and address key uncertainties in system response.

Project objectives

- Identify current OMCR technology gaps using previously completed Floating Wind JIP projects as a basis.[1]
- Develop an overview of the technical maturity of selected OMCR concepts.
- For the selected OMCR concepts, undertake numerical model simulations for major component exchange using a hydrodynamic model to inform downtime modelling and tank test specification.
- Develop a tank test specification and criteria that could feed into a future OMCR concept assessment phase.

[1] Heavy lift offshore maintenance (Phase 3), Tow to Port Maintenance(Phase 3), Major Component Exchange with self-hoisting cranes (phase 5)

Methodology

Concept market review and concept down selection

A wide review of the available OMCR concepts was conducted. From the large range of concepts identified, approximately twenty concepts were taken forward for high-level evaluation and down selection. This initial screening was primarily based on suitability or scalability for 15 MW floating offshore wind turbines, availability of information, and active development.

These concepts were assessed across the ten categories listed below using a high-level weighted scoring approach. The concepts were evaluated separately for their applicability to both modular geared turbines and direct drive turbines.

- Turbine modification
- Availability/weather window
- Bottlenecks
- Direct cost of operation
- Health, safety and environment (HSE)
- Execution duration
- 15 MW scale applicability
- Development Status
- Company Experience
- Component coverage

Ultimately three classes of concept were shortlisted: heavy lift vessel (HLV), nacelle-mounted crane and elevator-style concepts. As part of down selection, it was decided to focus the study primarily on modular WTGs configurations, although some findings are applicable to direct drive.

Technology maturity assessment

The technology maturity assessment had two components: the development of concept-specific method statements for the down selected OMCR concepts, and a concept maturity assessment. Key to the delivery of this stage was focused engagement with three OMCR concept owners, providing a better understanding of the concepts, information on deployment practicalities, their development status, certification approach and commercial strategy. This involved a structured, iterative process, including discussions, questionnaires and data exchange with the concept owners. A method statement was developed for each concept, detailing task breakdown, durations, component transfer weights and environmental limits. The method statements were informed through the collaborative discussion and reviews with the concept owners to ensure alignment with their proposed execution approaches.

The concept maturity assessment covered three high-level categories: concept development, compliance & regulation, and performance. These areas were selected to provide a balanced and holistic view of the potential success of the concepts under consideration. The approach combined desk-based research into relevant methodologies, industry practice and applicable standards, with direct input from the concept owners, drawing on their operational experience and considerations around development and commercial routes to market. The development pathway for each concept was compared with that expected for an OMCR solution to reach a similar level of maturity or readiness for deployment in fixed-bottom offshore wind. This comparison highlighted the key challenges and risks associated with reaching the level of maturity and readiness of current fixed-bottom OMCR solutions.

Numerical modelling

Two specific numerical modelling assessments were deployed:

1. OrcaFlex operation dynamic modelling; and
2. Downtime modelling using Total Renewables Insights Offshore (TRIOS), an in-house time series Monte Carlo operational model.

OrcaFlex was used to evaluate the workable environment for critical and restricted stages of the operation to verify, or challenge, proposed method statement weather limits and provide insight in the key critical dynamics of the operations for future assessment and validation.

The analysis primarily used a snapshot approach i.e. a fixed system configuration with dynamic environment, loading and system response. This approach was applied for three different floating foundation types: tension leg platform (TLP), semi-submersible platform and asymmetric semi-submersible. Critical stages of each operation were identified for each concept based on the method statements e.g. largest extensions, liftoff, touchdown etc. Each stage of operation was evaluated at significant wave heights (Hs) of up to 4 Hs (with the associated wind speed considering a suitable range of directions and seeds). Limits were determined for each operational stage and then combined. The most conservative limit (i.e. the minimum across all snapshots within that operation) was then noted and taken forward for consideration in the subsequent downtime modelling.

The TRIOS[2] model used for the downtime analysis is a time domain Monte Carlo simulation model that is used for forecasting operational performance of offshore wind farms. The high resolution of the TRIOS model allowed the full method statement for each component to be mapped directly into the model. The modelling considers operational sequence, wave height, wind speed constraints, and task duration.

The modelling assumes that only one MCR occurs at a time and that the required personnel, materials, tools and assets are available without delay. Availability estimates account for routine operation and maintenance (O&M), with baseline availability of 98% before MCR. Three studies were conducted: baseline availability, seasonal sensitivity and site-condition sensitivity. The effect of mobilisation, including commercial arrangements and practical deployment, was also assessed through post-analysis.

Tank test specification

The final step of this study was to develop a tank test specification suitable for validation of key dynamics prior to potential future deployment. This focused on the feasibility and key requirements of the tank testing for evaluating OMCR technology performance, including:

- measurements accuracy
- sensing requirement
- environment scale
- concept/foundation build feasibility
- suitable facilities
- programme optimisation
- critical physical phenomena
- indicative programme duration and cost

[2] TRIO Renewables. Link

Key assumptions

The following key assumptions were made for developing the study:

- A 15 MW turbine was considered.
- Three foundations were assessed, two Floating Wind JIP reference floating foundations (TLP, Semi-submersible), plus an additional asymmetric semi-submersible.
- Three OMCR concepts were assessed in the numerical modelling, which considered a modular turbine largest lift.
- Conditions were based on Floating Wind JIP moderate environment for dynamic modelling and specific ERA 5 location conditions for downtime modelling.[3]
- Downtime modelling considered a 50 x 15 MW turbine farm with a major component failure rate of 0.04.
- Concept properties used for modelling were used as given by the concept owners.

[3] ERA5 a global meteorological reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), providing long-term historical estimates of atmospheric conditions.

Key findings

1 Based on the stakeholder information provided all down selected concepts are considered technically viable although significant project and operational uncertainties remain.

- In dynamic analysis and downtime modelling the three shortlist concepts (HLV, Elevator, Nacelle crane) demonstrated they are able to execute the operation of the base case (i.e. a drivetrain component replacement) with a reduced downtime compared to TTS. Based on the information available to date they are considered technically viable, while recognising there are still significant uncertainties, risk inherent in early-stage development and system integration.
- The HLV solution provides high capacity and wide range of operation providing the most versatile solution, however the performance hinges on the effectiveness of the motion compensation system. There are also significant barriers to commercial deployment due to the large capital expenditure (CAPEX) and challenges associated with compatibility with scaling turbines. Given the scale and competition for other applications this is also expected to have the highest direct cost of operation.
- The elevator concept had consistent performance once installed, with additional infrastructure providing additional flexibility. However, significant installation work is required, with a number of large lifts dependent on support vessel performance, possibly creating bottlenecks. Of the concepts assessed, the elevator concept was at the earliest stage of technology development and required the greatest level of integration with the turbine and foundation. This currently presents a significant barrier to deployment, particularly in relation to turbine integration, as modifications to or impacts on the tower design are considered unlikely to be feasible in the near term.
- The nacelle crane solution was assessed as the most realistic near-term solution, based on the scaling of established crane technologies. Although adaption to specific turbine and foundation is required, the integration requirements are otherwise limited. The operation duration is expected to be longer than for an HLV-type solution. However, when considering the direct cost of operation and potential commercial availability delays, the nacelle crane solution is likely to be the lowest-cost option for operations that it can perform.

2 HLV type concept consistently performed best in direct MRC execution.

- Through method statement assessment and dynamic modelling, the HLV concept demonstrated the lowest complexity and shortest baseline duration of operation. This was primarily because no onboard concept installation is required, and the HLV has a greater reach and capacity, as well as a wider operating envelope compared to the other concepts considered.
- The results of the dynamic analysis showed an operability limit ranging between 1.5-3.5 m Hs, depending on foundation type. This wide range is due to the concept being limited by global platform motion. Given the high allowable lifting limits, it is likely other operational considerations, such as working limits within the nacelle, may drive the allowable operation limits rather than the lift itself. However, it is important to note that the overall system performance is reliant on the performance of the motion compensation system. Therefore, practical implementation my result in lower performance than the idealised performance modelled.
- An illustration of the impact of the wider operation limit of the HLV compared to other OMCR concepts can be seen in Figure 2.

- While the nacelle crane and elevator concepts both require more complex operations involving multiple onboard lifts, they mitigate global displacement challenges and are driven more by acceleration and motion. However, without additional support system or guide motion compensation, these were found to have a relatively restrictive operational window with execution only being feasible up to 1m Hs.
- Concept installation was identified as a particular bottleneck for the elevator type concept, which required a larger number of heavy foundation level lifts, often with a large reach (foundation dependent). Some limitations could be mitigated through a higher-specification support vessel, although this requires a trade-off between operational cost, weather restrictions and the risk of commercial delay.

3 Concept availability and therefore commercial approach is relevant to future viability.

- Mobilisation time was determined to be a significant factor affecting concept availability. In the baseline downtime study, the maximum variation in lost revenue across the concepts was equivalent to 2-3 months of loss production from a single turbine.
- Delays associated with availability are expected to be highest for the HLV concept, reflecting market availability and competition, similar to what is experienced in the jack-up market. Elevator concepts may also face availability constraints due to their dependence on the limited availability of larger capacity vessels. Nacelle cranes are expected to face the lowest availability risk, given their lower anticipated CAPEX and potential for higher-volume deployment. Given the scale and cost for elevator and nacelle mounted solutions, alterative ownership models might be feasible.
- Given the larger vessel requirement, the trend in direct operation cost is expected to follow the same ranking as commercial delay risk: HLV, elevator, nacelle crane. Therefore, where a nacelle crane concept can perform a reactive or near-term replacement operation, it is likely to provide the lowest overall cost, whereas potential extend scheduled replacement campaigns might see more benefit from the faster HLV execution and one-off commercial delay.
- Figure 1, illustrates this impact. The solid, bright colouring indicates the average execution time observed, with the light colouring showing and indicative nominal relative wait time risk. In this case, the HLV and elevator solutions show similar overall durations, while the nacelle cranes show a significantly lower duration. TTS was not formally assessed in this study. However, an indicative benchmark was included based on research studies of Kincardine TTS events, conducted by the University of Strathclyde.[4] A useful parallel can be drawn with fixed-bottom offshore wind, where jack-up vessel waiting times of 12 to 18 months are not uncommon, so a significant uplift in waiting time for limited availability concepts is not unreasonable and as noted may be significantly higher than execution durations.

[4] Saeed, K., Corgosinho, L. D. M., Collu, M., & McMillan, D. (2026). Analysing the worlds first major component replacements on floating offshore wind turbines. *Journal of Physics: Conference Series*, *3224*(6), Article 062076. Link

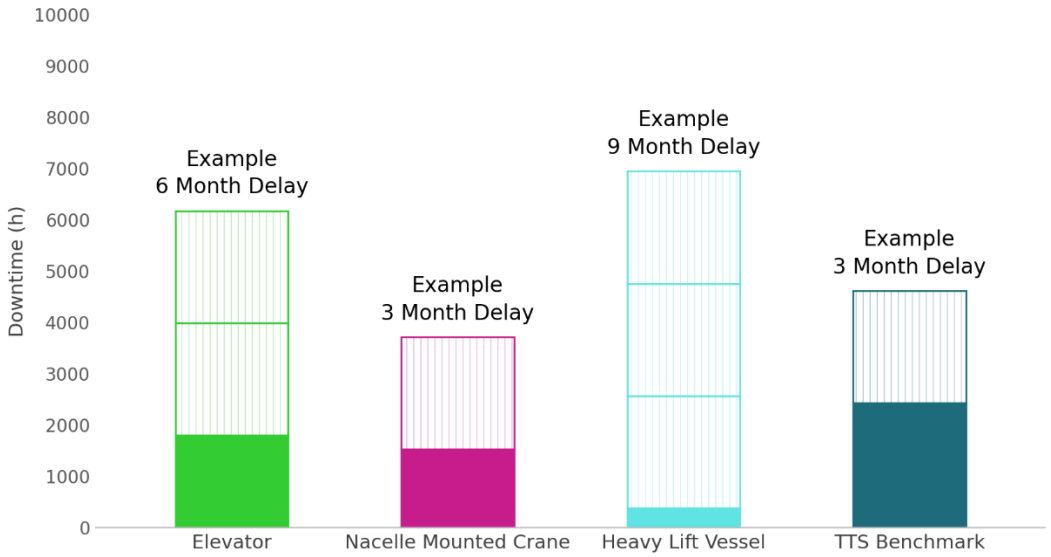


Figure 1: Overall downtime considering concept mobilisation delays. The bright solid colouring indicates the execution time, and the semi-transparent fill is used to illustrate a relative delay risk between different potential concept availabilities.

4 Further solution detailing and support systems are required and should enhance performance.

- The base-case dynamic and downtime analysis indicated that the concepts are viable, providing a competitive or improved performance to TTS. However, site condition and seasonality studies showed significant sensitivity, highlighting risks associated with the current performance levels. This is illustrated in Figure 2, which shows the impact of going from a baseline to severe site conditions.[5]
- The HLV solution, with the widest weather window, was the most resilient to this change. In contrast, nacelle crane and elevator solutions were highly sensitive, with durations increasing several-fold. Similar sensitivity was observed for failure in specific seasons, with failures outside the summer period all resulting in increased average downtime per failure due to worse environmental conditions.
- As the concepts are still in relatively early development stages, full operation details such as interface guides, transfer systems, enhanced control solutions, and tagline use/layout, have either not yet been developed or could not be shared with the project. The dynamic modelling was based on the current definition and fidelity approach for the nacelle crane and elevator concepts, and additional indicative or arbitrary constraints and stability measures were not applied. Performance improvement may therefore be expected as the technology designs mature.
- Even a relatively modest improvement in allowable operating conditions through additional transfer systems and guides would significantly improve the robustness of the solutions, particularly by improving sensitivity to site conditions and seasonality. This was explored in more detail with the concept owners for the most critical operational stages. The concept owners considered it feasible to design and deploy additional operational solutions, such as taglines and transfer systems or guides, if ultimately required to improve the operational window of the critical stage.

[5] Two ERA 5 data sets were used n56.75 e-1.75 and ERA5 n57.50 e0.00 broadly consistent with the FLWJIP Moderate and Severe conditions created as part of previous FLWJIP projects.

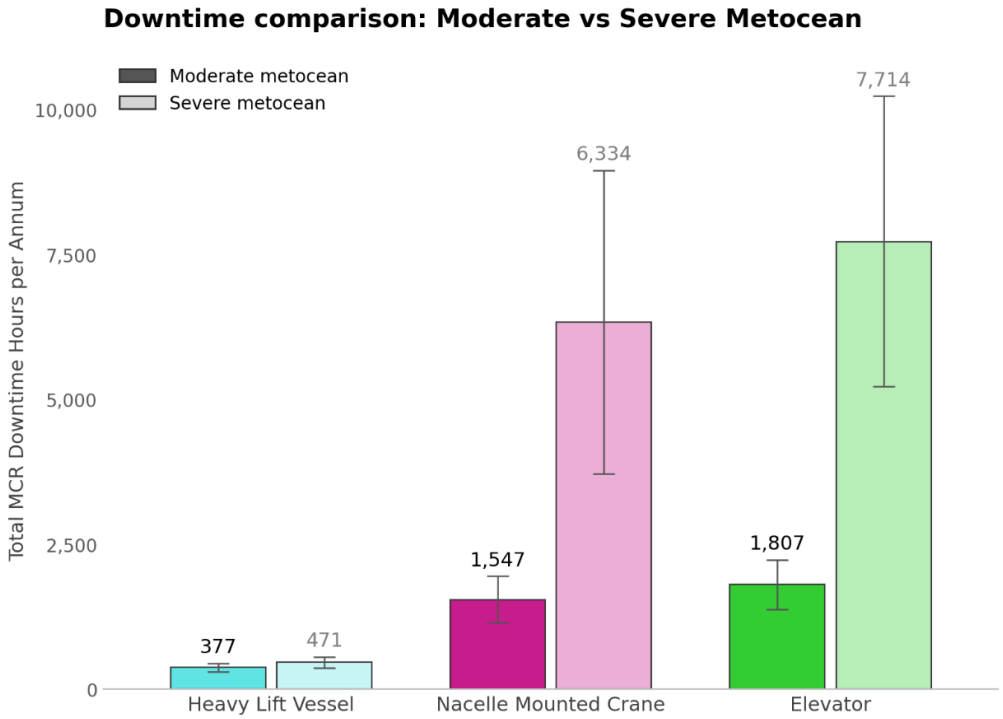


Figure 2: Downtime sensitivity analysis under moderate and severe site metocean conditions.[5]

5 Focused tank testing would enhance confidence and gauge conservatism ahead of deployment.

- While demonstration and fixed offshore deployment is likely the most valuable next steps to prove concept technologies for FOW, a focused tank test programme could be used to target specific risks and model uncertainties and provide greater confidence in modelled results and ultimate deployment.
- An initial focused tank test programme of around two weeks would be suitable to evaluate the critical aspects of one OMCR concept and give an overview of model conservatism and inform requirement of calibration of future modelling work.
- Tank testing would specifically derisk uncertainties from multi-body interactions, damping of low amplitude motions, new OMCR concept hydrodynamics, local wave fields and suspend load control implementation and load transfer, which are more challenging to accurately evaluate in numerical modelling. Model test validation will also provide further confidence in approaches and may reduce additional conservatisms otherwise required by project certifiers, marine surveyors or lenders.

Industry needs/innovations

1 Enabling requirements for OMCR should be considered at an early project stage.

- Stakeholder feedback indicated most conditions can be accommodated at the design phase, but there is an associated effort and cost to defining and deploying these enhancements.
- It also highlighted that requirements for supporting OMCR were not clear or consistent. Clearer, more standardised requirements are needed if they are to be considered in foundation design processes and lead to OMCR ready foundations/Floating Offshore Wind Turbine (FOWT) systems.
- While any modifications to support MCR need to be balanced against their impact on CAPEX, early consideration of MCR requirements can help manage life cycle cost, inform risks and reduce the chance of a step change in project economics as the FOWT system definition is refined throughout the project.

2 Multiple MCR solutions should be considered at site level.

- There is no single best solution even considering a single foundation type. The most suitable solution will depend on turbine technology (modular or direct drive), component and operation requirements, season, and commercial availability.
- Multiple solutions may therefore be required to ensure a robust and optimised O&M strategy, depending on the component, time of year, and concept availability. This should be considered during early project definition.

3 Operational limits should be treated as a starting point, not a fixed constraint.

- As outlined in the conclusions, the current weather limits reflect a combination of underlying assumptions and the present stage of concept development. As OMCR concepts are further developed, tested and demonstrated, these limits may be increased.
- Each operational stage should be examined individually to identify where design or mitigation measures could realistically widen the operating window.
- At this stage in concept development and deployment, the focus should remain on assessment via physical behaviours (including motions, accelerations and loads), rather than aggregated weather limits. This is particularly important given the variation in FOW foundations, the novelty of concepts and the limited operational experience in FOW. A constant weather limit approach for different FOWT system configurations may therefore not be applicable.

4 Stakeholders should be engaged on physically grounded lifting and operation requirements.

- While the physical limits used were informed by industry engagement and experience, there is limited availability of physical limits for FOWT operations. Given sensitivity of performance to these limits, it is important that concept owners work to consistent and appropriate tolerance requirements. However, greater clarity on these requirements is needed to enable solutions to be accurately compared and confidently applied. This requires:
    a. More transparency on the critical drivers, tolerance limits and lift capacities for specific components from WTG OEMs. These should be grounded in physical limits as floating configurations may alter previous independent crane/foundation performance definitions.
    b. Greater consideration of OMCE requirements by OEMs during design e.g. suitable inspection points.
    c. Consideration of non-lifting factors, such as workability within the nacelle.
    d. Specific attention to these requirements for floating offshore wind, given its broader range of system dynamics.

ABOUT THE FLOATING WIND JIP

The Floating Wind Joint Industry Project (Floating Wind JIP) is a collaborative research and development (R&D) initiative between the Carbon Trust and 17 leading international offshore wind developers: bp, EDF Renouvables, EnBW, Equinor, Kyuden Mirai Energy, Ørsted, Ocean Winds, Parkwind, RWE Renewables, ScottishPower Renewables, Shell, Skyborn Renewables, SSE Renewables, TEPCO, Tohoku Electric Power Company, Total Energies and Vattenfall.

The primary objective of the Floating Wind JIP is to overcome technical challenges and advance opportunities for commercial scale floating wind. Since its formation in 2016, the programme scope has evolved from feasibility studies to specific challenges focusing on:

3. Large scale deployment
4. De-risking technology challenges
5. Identifying innovative solutions
6. Cost reduction

Stage 3 of the Floating Wind JIP commenced in 2022 and projects are expected to run until early 2027. With several commercial scale floating offshore wind farm projects in design phase and having the ambition to be commissioned by 2030, the industry needs to address several challenges. The 17 Floating Wind JIP partners agreed on six research areas where further understanding and advancement is required to reach full commercialisation of floating offshore wind projects.

Electrical systems	Mooring systems	Logistics	Windfarm optimisation	Foundations	Asset Integrity and monitoring

This Onsite Major Component Replacement project addresses the ambitions of the Logistics research area:

Logistics

1	Understand the required port developments for commercial scale floating wind farms assembly.
2	Understand how water depth and environment affects the entire installation process.

The Stage 3 summary reports can be found here: Phase I, Phase II.

ABOUT THE CARBON TRUST

Who we are

Our mission is to accelerate the move to a decarbonised future. We are your expert guide to turn your climate ambition into impact.

We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions to drive positive climate action. To date, our 400 experts globally have helped set 200+ science-based targets and guided 3,000+ organisations and cities across five continents on their route to Net Zero.

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