FLOATING WIND JOINT INDUSTRY PROGRAMME

# Maximum Operating Sea-state Evaluation

February 2025

# Contents

Authors:

**Alistar Morris**
Manager, Carbon Trust
alistair.morris@carbontrust.com

**Luisa Amorim**
Manager, Carbon Trust
luisa.amorim@carbontrust.com

**Jack McDonald**
Senior Engineer, Amog Consulting
jack.mcdonald@amog.consulting

**Frank Lemmer**
Director, Sowento
lemmer@sowento.com

**Danai Skandali**
Senior Engineer, Sowento
skandali@sowento.com

## Acknowledgments

The Carbon Trust wrote this report based on an impartial analysis of primary and secondary sources, including expert interviews.

The Carbon Trust would like to thank everyone that has contributed their time and expertise during the preparation and completion of this report. Special thanks goes to: Shell, Japan Marine United, PelaStar, Glosten, Siemens Gamesa Renewable Energy, General Electric.

# Introduction

The Maximum Operating Sea-state Evaluation (MOSE) project was delivered by a consortium led by AMOG, together with Sowento and London Marine Consultants (LMC), which provides both floating wind and Oil and Gas experience. The project, delivered through the Floating Wind Joint Industry Programme (Floating Wind JIP), investigated the concept of a Maximum Operating Sea-State (MOSS), above which the turbine shuts down (similar to the cut-out windspeed), to reduce the design loads on the Floating Offshore Wind Turbine (FOWT).

Reducing the design loads on the system can allow for lighter, cheaper structures, thereby reducing the upfront cost (CAPEX) of a floating wind farm. The MOSE project was initiated to understand trade-offs between load reduction and impact to Annual Energy Production (AEP), as well as to identify the key design considerations when implementing this operating philosophy. This summary report outlines the project's key findings and highlights future requirements for the industry.

## Project objectives

1. Understand the potential cost savings for unit design by using Maximum Operating Sea-States (MOSS).
2. Define and outline a process by which MOSS can be optimised during project implementation.
3. Evaluate potential implementations of MOSS within the floating wind control and safety system by using robust and reliable sea-state sensors.
4. Identify the design considerations, especially metocean conditions and simulation lists, when using MOSS.

# Methodology

### Standards Review & Gap Analysis

Design Standards, Guidance Notes, and Recommended Practices were reviewed to identify the permissibility of MOSS, Design Load Cases (DLCs) that are affected by MOSS, as well as potential gaps and ambiguities.

### Functional Safety Analysis

Hazard Identification (HAZID) and Layers of Protection Analysis (LOPA) were conducted to determine the required Safety Integrity Level (SIL) for the MOSS system.

### Wave Measurement Technologies

A broad range of wave measurement techniques and sensors were reviewed. The Technology Readiness Levels (TRLs), capability, accuracy, and relative cost factors were compared to develop different approaches to measuring the sea-state for the purposes of MOSS limit exceedance detection.

### Stakeholder Engagement

Interviews with Original Equipment Manufacturers (OEMs), wave sensor manufacturers and floater manufacturers were conducted. These provided inputs at various points during the project, ranging from review of the HAZID activities, guidance around governing load cases for tower/floater design and capabilities and limitations of wave sensors.

### Loads Analysis

Time-domain analyses of the FOWT were conducted to derive the tower base loads with and without MOSS for comparison and quantification of the load reduction. The Floating Wind JIP 15MW semi-sub platform was used as reference design. A set of met-ocean data (hindcast) from a North Sea site was used as the basis for the assessment, the scope of which included:

1. Derivation of load cases covering the conventional DLCs and additional cases across the environmental contour, to obtain a holistic “response surface” – a response as a function of different combinations of wind and wave conditions. ;
2. Development and tuning of a normal-stop routine in consequence to cut-out sea-state exceedances;
3. Coupled analysis using OpenFAST;
4. Sensitivity analysis involving comparison of the reference stiff-stiff tower with a soft-stiff tower design and scaled-down environmental conditions (to simulate a more benign region).

### Comparison of MOSS Approaches

“Reactive” vs “proactive” MOSS approaches were compared. “Proactive” approaches measure the sea-state ahead of the turbine, with sufficient forewarning to shut down before the waves reach the FOWT. A “Reactive” approach is a risk-based method that involves short-term historical in-situ measurements and statistical analysis to estimate the likelihood of an upcoming MOSS limit exceedance.

Sea-state “rise times”, FOWT response correlation with peak wave elevations, and literature around averaging windows were also reviewed to formulate guidance around the most effective strategy, and determine which approach had the lowest impact on the expected uptime. The pairwise comparison was used to evaluate different MOSS implementations across a range of criteria and recommend the preferred approach.

### Development of Guidance & Recommendations

Design considerations and impacts of MOSS were identified and reviewed, and guidance for MOSS implementation was formulated based on the identified factors and outcomes of the analysis.

### Key Assumptions

The following key assumptions were made for simulation studies:

- The largest loads occurred in normal operation and extreme sea-state (DLC1.6) for the semi-sub platform considered, which was already found in The Carbon Trust's Phase III Numerical Modelling Guidelines Project;
- The reference designs considered were compliant in Fatigue Limit State (FLS) and Ultimate Limit State (ULS)/Accidental Limit State (ALS). A water depth of 150 m was considered, with site conditions based on a hindcast from a North Sea site;
- For the purpose of comparison of the two MOSS approaches (proactive vs. reactive), idealised sensors were assumed, with no delays or restrictions on power and communications.

# Key findings

## 1

## Use of MOSS is permitted by current Design Standards, however there is some ambiguity and gaps regarding the implementation.

- Several DLCs can be adjusted with MOSS. Depending on the DLC, it is possible to lower the wave height to the MOSS limit, assess with the turbine idle instead of operating, or apply a lower partial safety factor due to it being considered an abnormal condition. These modified load cases are the primary way by which MOSS can reduce the design loads on the FOWT.
- It is unclear in standards whether MOSS should be considered part of the control system or protection system. Shutdown events triggered by protection systems are typically subject to limitations on automatic restarts (although this depends on the exceedance condition), which may excessively penalise AEP if the same limitations are applied for MOSS limit exceedances. MOSS, however, is most analogous to the cut-out windspeed, and could be characterised as such by design standards.

## 2

## MOSS has benefits when there is a combination of high operational thrust and high sea-state as the governing design condition.

- The fundamental of MOSS is that the maximum ULS loads are driven by a combination of high thrust and wave loads, and that the ULS loads are governing the design of the component(s) of interest. Before considering using MOSS, the designer should understand which load case is driving the design. If DLC1.6 (which corresponds DLC 1.6 of IEC 61400-3-2)1 is the governing case, then MOSS can be considered as a tool to reduce design loads.
- The optimal MOSS system would limit the operation of the turbine such that DLC 1.6 is no longer the governing load case, as shown in Figure 1. As the overall utilisation of the specific system decreases, a design iteration can then take place to optimise the amount of material required, reducing the cost of each individual unit and therefore reducing project CAPEX.
- Imposing a MOSS limit on the FOWT will also reduce the expected uptime of the Wind Turbine Generator (WTG) and consequently the average AEP. Therefore, a designer should only implement MOSS when there is a net benefit to the Levelized Cost of Electricity (LCOE); where the trade-off between the lost revenue due to reduced uptime and cost savings from MOSS is favourable.

---

[1] (PDF) Guide for Building and Classing Floating Offshore Wind Turbines, American Bureau of Shipping

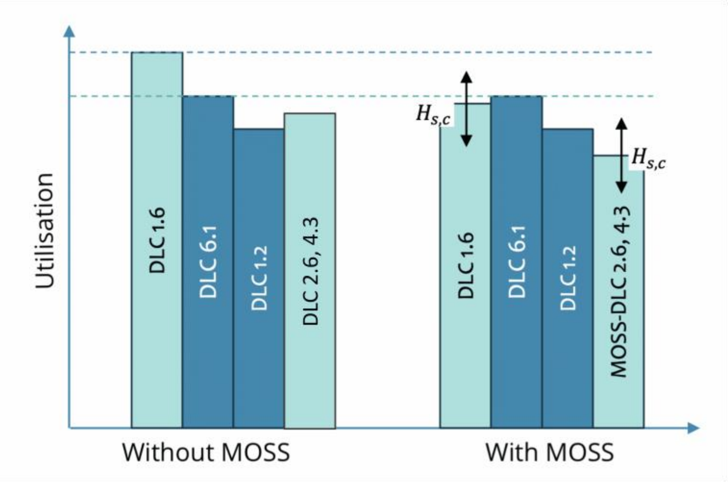


*Figure 1: MOSS-induced Load Effects*

## 3

## Integrated Loads Analysis and a holistic design approach is recommended if using MOSS. Secondary impacts of reducing the structural size must also be considered.

- MOSS aims at lowering the ultimate design loads on components to reduce the structural sizes and mass. However, reduction in structural size will have secondary impacts on other aspects of the performance of the components, such as fatigue performance, platform stability, platform offset envelope, and AEP, which must be considered when implementing MOSS.
- The implementation of MOSS also requires the consideration of various load effects and the contribution of different environmental loads to the system's response. A wide range of environmental conditions in the design contour should therefore be assessed. This is to ensure that the response of the FOWT at and above the MOSS limit is well understood by the designer, and allow identification of the governing conditions and accurate assessment of the impact of MOSS.
- MOSS should be considered early in the design phase, when initial Pre-Front End Engineering Design (FEED) analysis shows what is the driving load case. The design-driving load cases for each component of the FOWT, however, depend significantly on MOSS, and thus an iterative approach is recommended when designing a system that utilises MOSS.

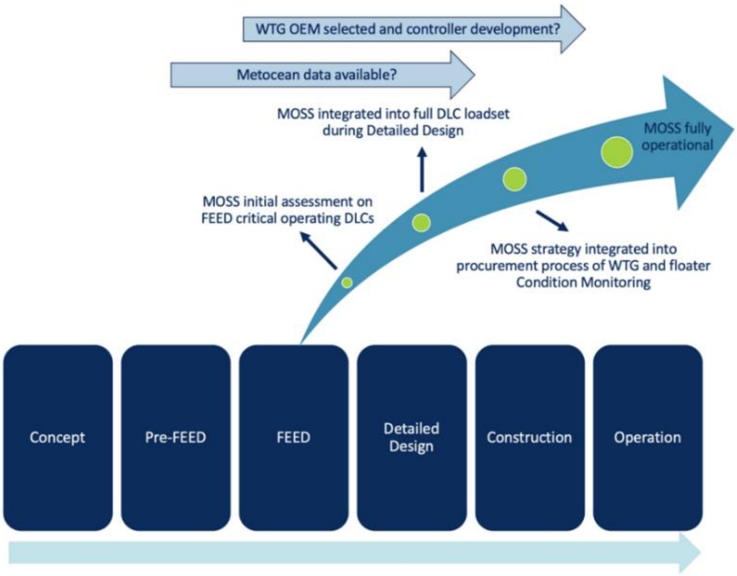


*Figure 2: MOSS During the Design Process*

**4** **A proactive approach using an array of wave buoys placed upwave of the farm, at sufficient distance and spacing to ensure directional coverage, was the preferred approach.**

- Reactive (risk-based) approaches inherently require a more conservative MOSS limit to achieve a given probability of non-exceedance (i.e. the probability that the sea-state does not exceed the MOSS limit in the next time period) than a proactive approach. This results in a greater impact on the expected uptime of the turbine and AEP.
- Furthermore, a reactive approach may fail to predict severe, sudden storm conditions prior to it reaching the FOWT, whereas a proactive system can detect oncoming adverse conditions ahead of time.
- The upwave buoy array should be designed to ensure coverage across all of the prevailing wave directions, especially for severe sea-states.

**5** **Redundancy, calibration and performance integrity requirements should all be considered for a MOSS system.**

- The MOSS system is considered critical to the safe performance and operation of the FOWT. To meet the required performance integrity level, redundancy should be considered and implemented by using multiple wave buoys.
- Wave buoys are subject to power and communication limits, which restricts how frequently they can communicate with the turbine control system. Constant remote communication (radio, cellular, satellite, or otherwise) is not currently feasible for long-term deployment in a MOSS system.
- Wave buoys will require calibration throughout the lifetime of the farm and may also require cleaning from biofouling to ensure accurate measurement of the sea-state.

## 6 Short term sea-state (height and period) information provides the most accurate and feasible environmental information for a MOSS system

- Poor correlation was predicted between individual peak wave events and the peak FOWT tower base bending moment response. While there was a phase relationship between 1st-order wave loads and the tower base bending moment, the overall peak magnitude in the response was driven by low-frequency thrust loads.
- This finding, combined with the power and communication restrictions for long-term deployment of remote sensors, results in the recommendation that short-term sea-state averaging should be used instead of using individual peak wave events.
- An average window of 30 minutes is recommended based on literature review of sea-state stationarity, consideration of uncertainty in sea-state measurements, and wave buoy capabilities.

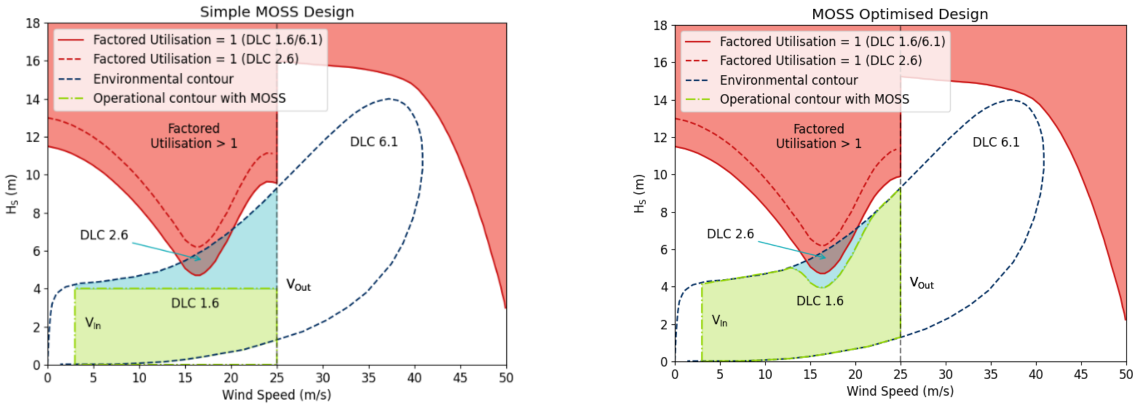
# Industry needs/innovations

**1** **Innovations in WTG control systems could achieve similar load reductions while minimizing the impact to AEP.**

- Governing load cases are often driven by the maximum thrust loads from the turbine. Rather than fully idling the turbine above the MOSS limit, modified control systems that derate the turbine (to operate in a lower thrust mode) in these conditions could be used as an alternative. By allowing the turbine to operate in reduced thrust mode above the MOSS limit instead of complete shutdown, which may otherwise be too penalising for the AEP, these modified control systems would minimise the impact on AEP while still providing load reduction.
- There is further opportunity for hull & mooring cost optimisation if MOSS can be combined with a wind turbine controller tuned to reduce fatigue on the moorings, without the need for additional software or hardware. This could enable a reduction of both ultimate and fatigue design loads. Especially for benign sites, lightweight FOWT designs might be possible with a combination of MOSS and a fatigue-reducing controller and should be further investigated by industry.

**2** **Multi-variable operational limits could provide a load reduction while minimizing the impact to the uptime of the turbine.**

- A MOSS limit defined by significant wave height alone is potentially overconservative. Above rated wind speeds, the control system starts to pitch the blades, which reduces the rotor thrust. For this reason, a more optimal strategy could depend on the combination of wave height and wind speed, as opposed to the wave height alone. Figure 3 illustrates this concept, in which the operational contour (green) is significantly larger when selectively excluding high-utilisation cases based on significant wave height and windspeed combinations, compared to a simple wave height limit. Additional parameters, such as wave period and direction (as well as wind-wave misalignment), are also likely to have an influence and could be considered.
- A multi-variable operational limit could optimise the selection of shutdown conditions, achieving load reduction while minimising the impact to uptime. However, this will require additional design effort to ensure the turbine response is well understood across the design space and all combinations of variables.



a) Simple MOSS design with a single $H_S$ limit

b) More optimal MOSS design with a $H_S$ and windspeed dependence

***Figure 3. MOSS optimisation by including windspeed dependence. Figure modified from Haselsteiner, A. F., Frieling, M., Mackay, E., Sander, A., & Thoben, K.-D. (2021)[2]***

## 3

## The potential benefits of MOSS for mooring and cable design should be explored further.

- Whilst the focus of the numerical analyses conducted in the project was for the impact of MOSS on the FOWT structure specifically, there are opportunities for optimising dynamic cable and mooring design by implementing MOSS.
- If the maximum platform offsets are driven by high thrust loads combined with a severe sea-states, then introducing MOSS may enable reduction of the offset envelope, leading to cheaper cable designs, or a reduction in the required size and stiffness of the mooring.

---

[2] Long-term extreme response of an offshore turbine: How accurate are contour-based estimates? *Renewable Energy*, *181*, 945–965. https://doi.org/10.1016/j.renene.2021.09.077

## ABOUT THE FLOATING WIND JIP

The Floating Wind Joint Industry Programme (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:

- Large scale deployment
- De-risking technology challenges
- Identifying innovative solutions
- 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 Maximum Operating Sea-state Evaluation project addresses the ambitions of the e.g. Windfarm optimization research area:

### Windfarm optimisation

| | |
|---|---|
| 1 | Assess technology developments such as ballast, sizing and cost to support with both floater and tower developments. |
| 2 | Understand floating specific windfarm layout and turbine specific developments to maximise yield. |
| 3 | Define floating specific controllers and modifications required in context to floating specific turbines. |

The Stage 2 summary reports can be found here: Phase I, Phase II, Phase III, Phase IV and Phase V.

## 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.

**carbontrust.com**

**+44 (0) 20 7170 7000**

The Carbon Trust is a company limited by guarantee and registered in England and Wales under Company number 04190230 with its Registered Office at: Level 5, Arbor, 255 Blackfriars Road, London SE1 9AX, UK.

Published in the UK: 2025