

FLOATING WIND JOINT INDUSTRY PROGRAMME

Ballast Systems for Stability Control of Floating Platforms

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Authors:

Luisa Amorim
Manager, Carbon Trust
Luisa.amorin@carbontrust.com

Karolina Zieba
Senior Associate, Carbon Trust
Karolina.zieba@carbontrust.com

Frank Lemmer
Director, Dr.-Ing., Sowento
lemmer@sowento.com

Marian Albers
Senior engineer, Dr.-Ing., Sowento
Marian.albers@sowento.com

Albino Pombo Silva
MSc Naval Architect, Seaplace
apombo@seaplace.es

Ignacio Segui Davalillo
Naval Architect, Seaplace
isegui@seaplace.es

Santiago Bueno Infantes
Naval Architect, Seaplace
sbueno@seaplace.es

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BALLAST SYSTEMS FOR STABILITY CONTROL OF FLOATING PLATFORMS (BSSC)

Introduction

Ballast systems are used on floating platforms to control stability by managing the amount and distribution of ballast (typically seawater) within onboard tanks. By adding, removing, or transferring ballast, these systems regulate the platform's draft, trim and heel to ensure it remains upright, stable, and safe under changing environmental and operational conditions throughout installation, operation, and decommissioning. Passive ballast systems use fixed or externally filled tanks to set a baseline stability condition and are not adjusted during normal operation, while active ballast systems (ABS) use pumps, valves, sensors and control systems to automatically adjust ballast in real time. Many modern designs adopt hybrid configurations, combining permanent passive ballast with active system capable of internal water transfer and intake or discharge to optimise platform performance.

Robust ballast systems play a critical role in optimising the operation and energy generation of floating wind platforms by enabling greater control of platform motions and improving stability characteristics. This enhanced stability can contribute to improved wind turbine generator (WTG) efficiency, particularly under dynamic conditions. Such functionality becomes increasingly important in regions characterised by harsh marine environments, where rapid and unpredictable motions driven by fluctuating wind and wave conditions pose significant challenges to operational safety and performance.

While ballast systems offer clear advantages, their integration introduces a range of technical and economic considerations that must be carefully assessed. These include, but are not limited to:

- The cost of hardware and impact on energy consumption.
- Complexity, sensitivity and responsiveness in design.
- Impact on wind turbine generator performance and annual energy production.
- Maintenance requirements, considering failure rates.

The project, delivered by Seaplace and Sowento, was initiated to evaluate the benefits, limitations, and lifecycle implications of different ballast system configurations for floating offshore wind platforms. The scope encompassed a cost-benefit analysis of alternative designs, identification of equipment requirements and operational procedures, and the development of an operations and maintenance (O&M) strategy for the full system lifetime, including the identified ballast systems.

A key driver for considering an Active Ballast System (ABS) in a Floating Offshore Wind Turbine (FOWT) is its ability to maintain tower verticality regardless of wind speed or the overturning moment induced by rotor thrust forces. Preserving an upright tower minimises cosine losses - performance losses that occur when the rotor is misaligned with the wind direction - thereby improving overall energy yield. However, these benefits must be weighed against the complexity and cost implications of implementing these systems, as well as their influence on floater design and long-term reliability.

Project objectives

1. Investigate current and emerging state-of-the-art ballast systems for FOWT platforms to understand the advantages, disadvantages and limitations of various advanced systems for different wind turbine platform archetypes.
2. Undertake a cost-benefit analysis through various stages of the system lifecycle, including costs associated to risk mitigation, to understand the benefit of ABS compared to passive ballast systems.
3. Investigate the requirements and procedures for associated systems and equipment, and how these need to be adapted for varying metocean conditions and environments.
4. Define an operations and maintenance strategy for the lifetime of the identified ballast systems.

Methodology

Literature review and stakeholder engagement

Literature review and stakeholder engagement were conducted to establish a clear understanding of the state-of-the-art in ballast system technologies. Interviews with platform designers, equipment manufacturers and a classification society were used to capture insights on current market solutions as well as emerging alternatives.

Each ballast system was characterised in terms of its ability to manage temporary conditions, maintain stability under damaged scenarios, and compensate for turbine thrust forces. This qualitative assessment provided the foundation for subsequent quantitative analysis.

Simulations

Simulations were aimed at quantifying the technical and economic trade-offs of incorporating ABS into floating offshore wind platforms. The analysis was performed using coupled aero-hydro-servo-elastic modelling in OpenFAST, supported by ultimate and fatigue load assessments, damage stability evaluations, and a detailed cost model to estimate Levelised Cost of Energy (LCOE). A comprehensive lookup table of cosine losses was developed for a 15 MW reference turbine, covering a wide range of operational conditions.

The site selected for this study was located in the North Sea, with representative metocean conditions and load cases defined to reflect realistic deployment scenarios.

It is important to note that the design of an ABS is linked to the floating platform configuration. This study therefore focused on a single substructure type, a semi-submersible floater, to ensure consistency and depth of analysis. Two benchmark designs were evaluated:

- Reference design with passive ballast, featuring a platform mass of 16,517 tonnes and a static pitch of 4.2° at rated wind speed.
- Larger Static Pitch Angle (LSPA) design, developed as part of a Floating Wind JIP study¹, featuring: ABS, a reduced platform mass of 14,602 t and a static pitch of 8.5° at rated wind speed.

¹ Carbon Trust (2025) Large Static Pitch Angles - [Link](#)

Both configurations were coupled with a 15 MW turbine with a stiff-stiff tower design and a three-leg all-chain catenary mooring system. Control strategies were implemented using the Reference Open-Source Controller, supplemented by a supervisory controller for start-up and shut-down manoeuvres, developed by Sowento.

Specification of the ballast system architecture

A full piping and instrumentation diagram tailored to the floating wind turbine was developed alongside datasheets for all major ballast components. These specifications informed an updated cost-benefit analysis incorporating long-term operational parameters and performance during marine operations. A revised CAPEX estimate was produced based on the definitive ABS design.

Operations and maintenance

Reliability assessments, failure management strategies, and their impact on turbine availability and long-term Annual Energy Production (AEP) were developed to understand the implications of integrating ABS into floating offshore wind platforms. A dedicated O&M strategy was developed, combining predictive and corrective maintenance approaches to optimise system performance and minimise downtime.

Using updated CAPEX and OPEX data, alongside probabilistic failure modelling and smart operational strategies, the study quantified the net effect of ABS integration on LCOE.

Key findings

1

ABS can increase energy production by reducing mean tilt, providing >1% net AEP gain, especially at low-wind sites.

- The analysis showed that an ABS can provide a measurable improvement in energy yield by reducing tilt-induced losses, especially at low-wind sites or with flexible floater designs. When a floating platform tilts due to rotor thrust forces, the turbine rotor is no longer perfectly aligned with the wind direction. This misalignment causes cosine losses, reducing AEP. An ABS actively adjusts ballast to counteract this tilt, keeping the tower more upright and improving energy capture.
- The amount of AEP gains depends on a several factors. Sites with lower wind speeds benefit more because cosine losses are most significant in the partial-load regime (when the turbine operates below rated power). Platforms with larger static pitch angles (e.g., relaxed metacentric height designs) see a greater benefit because ABS compensates for higher tilt. Setting an upwind tilt target (around 2° for the reference design) provides the best balance between energy gain and operational robustness. For the reference design, AEP gains are typically 1-1.5% but can reach 3% for low-wind sites or platforms designed with reduced hydrostatic stiffness.
- ABS can enable lighter, more cost-effective floater designs by compensating for higher tilt angles, reducing the need for strict hydrostatic stability requirements. This means developers can lower CAPEX while maintaining acceptable energy performance. Overall, performance results indicate that ABS offers a consistent AEP benefit with a negligible energy consumption (relative to AEP gain) and may enable a broader range of floater designs by partially decoupling AEP considerations from hydrostatic stiffness.

2

A platform with relaxed metacentric height and ABS introduces additional load considerations during transient events, particularly shutdowns.

- During normal operation, ABS does not significantly increase turbine or platform loads compared to a passive ballast system. Certain operational manoeuvres – especially shutdowns at rated wind speed or in severe sea states – can cause higher transient responses when ABS is active. This is especially the case if the platform pitch equilibrium is further away from the operational platform pitch angle than without ABS.
- Combining ABS with an LSPA floater (with reduced hydrostatic stiffness) results in a larger pitch motion amplitude, which in turn increases structural loads. Therefore, ballast system faults represent new loads cases which should be evaluated during design phase.
- Shutdown load cases become more demanding with ABS and should be treated explicitly during design. ABS fault conditions (e.g., pump failure or control malfunction) must be included in Design Load Cases (DLCs) with realistic assumptions based on the ABS architecture. While operational loads remain within acceptable limits, structural checks are essential for softer floater concepts enabled by ABS.
- A stiff-stiff tower design may provide enough structural margin to accommodate relaxed metacentric height platforms without major reinforcements, allowing for CAPEX reduction.

3

ABS can play a valuable role in managing damage-stability scenarios by enabling controlled cross-flooding to prevent capsizing after hull damage.

- When a semi-submersible hull is damaged, the platform can lose stability and tilt significantly. Fitting an ABS allows controlled cross-flooding between ballast tanks, actively redistributing water to rebalance the platform and recover tilt.
- Two strategies were tested. Both proved effective in restoring stability after damage:
 - a. Automatic turbine shutdown before cross-flooding (conservative approach).
 - b. Continued turbine operation for a short interval during cross-flooding (more aggressive but still feasible approach).
- Traditionally, semi-submersibles rely on passive survivability, meaning they have multiple watertight compartments to limit flooding and maintain stability without active intervention. If active cross-flooding via ABS is part of the design philosophy, platforms may not need as many internal compartments, reducing structural complexity and weight. This can simplify construction and potentially lower CAPEX.
- This approach makes the ABS an active safety system, not just a performance enhancer. Therefore, the ABS must be highly reliable, and clear operational procedures must be in place for damage scenarios. Failure of the ABS during a damage event could compromise stability, so redundancy and fault management become critical.

4

A proper ABS design can achieve high reliability with low impact on turbine availability, thanks to built-in redundancy and well-defined and integrated repair strategies.

- A centralised ABS can be implemented using commercially available pumps, valves and control equipment, through a design that does not compromise the system's operational capabilities even in the case of any single component failure. The design includes redundancy features such as parallel pump branches, dual-valve tank connections and a double-manifold, which ensure that ballast transfers can continue even when individual components fail.
- The risk assessment using a fault-tree methodology showed a low annual probability of complete ABS loss, leading to a mean time between failures of around 40–50 years. Most failures are isolated and do not affect overall system functionality because of the redundancy in the design. Therefore, the impact of ABS failures on turbine performance remains almost negligible. Even under conservative assumptions, the long-term production loss associated with ABS failures was found to be <0.10 % per year, keeping turbine availability at levels comparable to passive ballast systems.
- These findings indicate that the ABS can be integrated into commercial floating wind platforms without introducing significant operational risk, provided redundancy features are preserved and clear repair strategies are adopted. In that case, ABS are a technically feasible and operationally reliable system, compatible with existing O&M practices.

5

Fitting an ABS is economically viable, with long-term LCOE savings due to moderate system costs, low O&M impact and measurable AEP gains.

- The economic assessment combined CAPEX, OPEX and long-term performance estimates to understand the financial implications of integrating a ballast system on a floating wind platform. The results showed that CAPEX costs remain low thanks to the use of conventional and commercially available equipment. Annual O&M needs for ABS appear to integrate cleanly into already existing turbine maintenance programmes.
- When these costs are combined with the previously mentioned increase in AEP, the integration of an ABS into a FOWT unit results in a net reduction in LCOE, effectively paying for itself through

performance gains alone. In scenarios where the ABS enables relaxed metacentric height floaters, the additional reduction in floater CAPEX further amplifies the savings (estimated at 5-15% floater CAPEX reduction), leading to total LCOE reductions of more than 2% in some cases.

- These qualified LCOE benefits do not include the wider qualitative advantages that an ABS provides across the floater’s lifecycle (such as those during assembly, wet storage, transport and installation, tow-to-port operations, hull inspection, decommissioning, etc.). Once these operational flexibilities are considered, the overall value proposition may become stronger.

Industry needs/innovations

1

Developing integrated turbine-floater-ballast control strategies to manage loads and enable softer floater designs is key.

- A key next step for the industry is the development of combined control strategies that explicitly consider the interaction between turbine pitch and torque control and active ballast operation. Future work could include:
 - a. Investigation of how integrated control can improve shutdown behaviour, reduce peak loads, and mitigate transient list during extreme or emergency events.
 - b. Establish best practises for turbine-floater controller integration, including minimum-level integrations (i.e. exchange of operational status, only).
 - c. Development of OEM-reviewed, co-optimised controllers where turbine and platform share real-time signals (tilt, ballast rate limits, shutdown triggers).
 - d. Development of robust contractual frameworks for yield and design liabilities of integrated turbine-floater systems.
- This work could reduce uncertainty in certification workflows and allow developers to safely exploit softer, lower-CAPEX floater designs.

2

Prioritisation of ABS adoption should consider site-specific AEP and LCOE assessment.

- The AEP benefit of ABS is highly site-dependent, especially in moderate-to-low wind resource regions where the effect of cosine losses is more pronounced. To support commercial decision-making, future activities could include:
 - a. Mapping of ABS gains using representative wind climates, floater concepts and controller settings.
 - b. Development of streamlined tools for AEP screening, enabling developers to evaluate ABS impacts during early-stage site selection.
 - c. Comparison of floater designs to identify which ones and what geographical areas would yield the largest LCOE improvements by incorporating an ABS.
- This work would help quantify where ABS provides the greatest value and guide developers on when the technology should be included as part of the baseline design.

3

There is a need to establish clear, industry-wide guidance for integrating ABS into floating wind design and certification.

- The project highlighted the need for clearer guidance on how to integrate ballast systems within the broader floating wind design process. Future work could focus on:
 - a. Defining industry-wide approaches for ABS sizing, target-tilt selection and ABS controller parameterisation. Because AEP gains and loads strongly depend on these settings, a consistent methodology would support technology comparability across projects.
 - b. Creating recommended practices for damage stability with active systems, ensuring alignment with certification bodies and future standards.
- Such guidelines would support a consistent approach across the industry, reducing technical uncertainty.

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 Renouvelables, 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 Ballast Systems for Stability Control of Floating Platforms (BSSC) project addresses the ambitions of the logistics research area:



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

3	Remove barriers to allow for commercial scale major component exchange offshore.
4	Understand how wet storage will be managed/addressed by the port and the wider industry.
5	Understand how the increase in ports bearing capacity requirements will be addressed by the industry.

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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+44 (0) 20 7170 7000

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