



POWER STORAGE IN D OCEAN

D3.5. ESS 2 KESS Kinetic Energy Storage System (Flywheel) for marine applications. Summary of the results achieved

Document Information	
Deliverable	Report on the KESS on-lab testing
Lead Beneficiary	ANTEC
Type:	R - Report
Work Package	WP3 ESS 2: KESS Flywheel.
Date	11/05/2026



Funded by the
European Union

This project is funded by European Climate, Infrastructure and Environment Executive Agency (CINEA), under the powers delegated by the European Commission under grant agreement Project: 101096457 – POSEIDON - HORIZON-CL5-2022-D5-01.

Dissemination level

Dissemination Level	
PU: Public	X
SEN: Sensitive, limited under the conditions of the Grant Agreement	

History

Version	Date	Reason	Revised by
1	30/04/2026	First draft	Ander Rodríguez Gustavo Navarro
2	11/05/2026	Final Version	Rafael Iturbe

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1. EXECUTIVE SUMMARY

This deliverable summarises the results achieved in WP3 for the development of the POSEIDON kinetic energy storage system (KESS) for marine applications. Within the Horizon Europe POSEIDON project, WP3 addressed the design, engineering, manufacturing and laboratory validation of a marinized flywheel-based storage module intended for fast-response services in waterborne transport. The work resulted in an integrated demonstrator based on a slow-flywheel architecture, specifically adapted to ship-motion constraints, onboard integration requirements and safety-by-design principles.

The main Key Exploitable Results obtained in WP3 are the following: a marinized KESS architecture for marine duty; a 20 kW-class integrated demonstrator with an operating range of 8,000–10,400 rpm, total stored energy of 9.7 MJ and usable operating energy of 3.97 MJ; a marine-oriented rotodynamic and bearing solution; a validated machine–converter–control chain; and a controlled-motion testing methodology relevant to ship applications. These results are relevant for short duty cycles in hybrid marine power systems, where fast power delivery and repeated charge/discharge cycles are more important than long-duration energy autonomy. In that context, the KESS is positioned for functions such as peak shaving, load leveling, grid frequency stabilization and the mitigation of fast transients during manoeuvring or hybrid propulsion support.

The laboratory campaign at CIEMAT demonstrated supervised start-up, acceleration, speed holding, inertial coasting, braking and coherent operation of the integrated control chain. The controlled-motion campaign at CEHIPAR (El Pardo Hydrodynamic Experiments Centre), located in Spain, added experimental evidence of the behaviour of the rotating system under representative vertical and rotational excitations linked to marine service. At the same time, the public evidence must be interpreted correctly: the results support functional and integration validation of an integrated laboratory demonstrator. Accordingly, the present maturity level is best described as an integrated demonstrator validated in laboratory and controlled-motion conditions, with further optimisation and onboard demonstration required for progression to higher TRL.

From a technical viewpoint, the main achievements of the work include the successful marinization of a slow-flywheel architecture, the definition and fabrication of a flywheel-machine-converter demonstrator, the implementation of a control strategy based on speed- and current-dependent ON/OFF switching angles for the switched reluctance machine, and the verification of the system behaviour under representative laboratory and motion-induced loading conditions. In parallel, the project integrated a dedicated safety process through WP6, where a risk-assessment methodology based on systems engineering and hazard elimination/minimization was planned for all FRESS technologies, including the KESS, to support intrinsically safer design and future onboard deployment.

2. INTRODUCTION

The POSEIDON project was defined to demonstrate the applicability of three innovative fast-response energy storage systems in waterborne transport: superconducting magnetic energy storage, flywheel-based kinetic energy storage and supercapacitor-based electrical energy storage. The project objectives explicitly include onboard integration, cost-competitiveness, efficiency and safety in relevant maritime environments, and WP3 is the work package devoted to the development of the flywheel-based solution. The project is funded by the European Union under the Horizon Europe Framework Programme, Grant Agreement No. 101096457, under call HORIZON-CL5-2022-D5-01.

Within this framework, the specific objective of WP3 was to develop and provide Innovative Output 2, namely a slow flywheel for waterborne transport. According to the Grant Agreement, the work was structured into three sequential tasks: Task 3.1 for modelling and design adaptation to waterborne conditions, Task 3.2 for fabrication of the full KESS including engineering design and factory acceptance activities, and Task 3.3 for final integration and on-lab testing at CIEMAT facilities, including tests related to torque, friction, heating, over-speed, vibration and controlled oscillation on a moving table.

The present deliverable corresponds to D3.5 and provides the public report summarising the main technical achievements related to the KESS for the maritime sector. Therefore, this document does not replace the detailed technical evidence already reported in D3.1, D3.2, D3.3 and D3.4, but rather consolidates their main results in a coherent public-facing summary focused on the achieved outcomes, the relevance for marine applications and the contribution to the overall objectives of POSEIDON. D3.5 is the final deliverable of WP3 and constitutes a comprehensive summary of all the main technical results achieved in the development of the KESS for marine applications. In accordance with the Description of the Action, this document must report the key outcomes of the design, engineering, manufacturing, testing and validation stages of the flywheel-based storage system, with particular emphasis on the aspects that differentiate the POSEIDON KESS from earlier terrestrial or offshore flywheel developments, namely its marinization for passenger ferry applications in the Mediterranean Sea.

The logic of the work carried out during WP3 followed a progressive maturity path. First, the consortium defined the environmental, mechanical and electrical constraints associated with a marinized flywheel for waterborne use; second, it transformed those requirements into a detailed engineering solution and a fabricated demonstrator; and third, it validated the integrated system through laboratory tests and controlled-motion experiments representative of vessel operation.

This progression is technically relevant because flywheel systems are mature in certain land-based sectors, but marine deployment imposes specific constraints that are not marginal. In the POSEIDON case, these constraints were mainly associated with ship motion, gyroscopic loads, vibration, humidity, space limitation, safety requirements and the need to integrate the KESS into a containerized and monitored onboard architecture.

The report also integrates the findings of the risk assessment carried out in WP6 (D6.3) specifically for the KESS technology, covering the hazard identification, consequence evaluation and mitigation measures implemented in the design. This integration is intended to demonstrate that the system was developed with safety and reliability as core design drivers, and that the identified risks have been addressed to levels considered acceptable for the intended marine application. □

3. FINAL KESS DESIGN AND ENGINEERING SUMMARY

3.1. OBJECTIVES, SCOPE, RELATION WITH WP3

The primary objective of D3.5 is to synthesise and communicate the key technical achievements accomplished within WP3 across all its constituent tasks, from initial design through laboratory validation, in a form suitable for evaluation by the European Commission. As such, this deliverable does not introduce new experimental or analytical work, but rather consolidates the results previously documented in D3.1 through D3.4 into a coherent technical narrative that demonstrates progress against the WP3 objectives. The scope of the deliverable is explicitly oriented towards the KESS technology, covering the following aspects:

- The final system architecture, key design choices and technical specifications of the marinized KESS demonstrator.
- The main engineering and manufacturing outcomes, including design changes introduced in response to technical findings during the project.
- The results of the Factory Acceptance Tests and the laboratory validation campaign, including the controlled-motion tests representative of marine service conditions.
- The findings of the risk assessment conducted in D6.3 for the KESS, with emphasis on hazard identification, consequence classification and mitigation measures embedded in the design.
- A summary of TRL progression, deviations from the original plan, and lessons learned that are relevant for the future development of the technology towards higher readiness levels.

3.2. DESIGN BASIS AND SELECTED CONCEPT

From the design stage, the POSEIDON consortium selected a slow-flywheel architecture as the most suitable solution for the targeted marine application. D3.1 and D3.2 state that the slow-flywheel approach was preferred over a fast composite flywheel because it is more robust for waterborne conditions, allows geometrically efficient isotropic metallic rotors, uses less demanding manufacturing tolerances, avoids the strong dependence on high-speed magnetic-bearing architectures, and is considered more appropriate for integration in vessels where the mass penalty is acceptable relative to ship deadweight.

In the case of kinetic energy storage systems (KESS), all these conditions affect to the design, but being a system based on a big rotary mass, the biggest challenge in the marinization of the system is how to deal with the movement of the boat and the gyroscopic forces that appear in the rotary system due to the boat movement. *Fig. 1* shows the typical movements that occur on a boat.

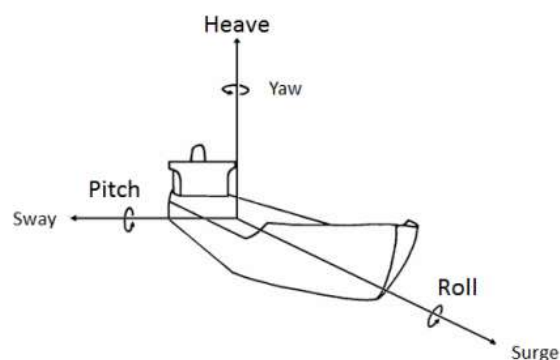


Fig. 1. Boat movements

Boat movements and the forces related to those movements can be separated in 2, linear movements with linear forces and angular movements with gyroscopic forces. The movements of the boat depend on the geometry of the boat, the waves and sea conditions and the load of the boat, but it can be generalized as the bigger the vessel, the higher stability and lower accelerations.

In the POSEIDON project, a passenger ferry with the normal operation between islands in the Mediterranean Sea will be the final target of the project. Based on the boat type and the sea conditions, two different conditions will be differentiated, the first one will be the nominal operation condition, and the second will be the extreme condition.

3.2.1. GYROSCOPIC FORCES

The wave disturbance induces rotational movement in the boat, roll and pitch mainly, as the flywheel is anchored to the boat, the movement of the boat induces precession motion in the flywheel [1]. The precession is the change in the orientation of the rotational axis in a rotational system, in this case, the change in the flywheel rotational axis. The precession is the cause of the gyroscopic torque in rotational system (see Fig. 2) [2].

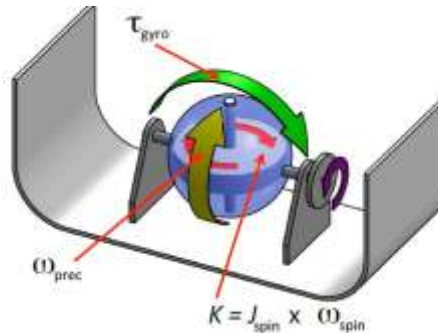


Fig. 2. Schematic image of gyroscopic forces.

The gyroscopic torque is described with the following equation.

$$\tau_{Gyro} = J_{spin} * \omega_{spin} * \omega_{prec}$$

Where τ_{Gyro} is the gyroscopic torque, J_{spin} is the polar inertial moment of the flywheel, ω_{spin} is the rotational speed of the flywheel, and ω_{prec} is the rotational speed of the boat.

3.2.2. NOMINAL OPERATION CONDITION

The nominal operation of the system will be on a ferry boat between islands. In this specific conditions, small waves up to 1.5m height are expected as normal condition. Fig. 3 shows the historical wave height data for the Balearic Islands.

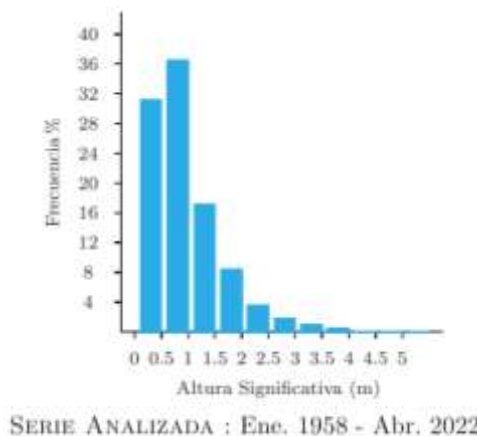


Fig. 3. Historic waves amplitude between Balearic Islands (from january. 1985 to april 2022).

Since the final geometric characteristics of the boat are not defined, conditions from "Measuring vessel motions using a rapid-deployment device on ships of opportunity" [3] will be used to estimate the boat motions. In this study the motion of a passenger ferry boat is studied but the average waves are higher than in the POSEIDON project, 2 to 3.5 meters against 1 to 1.5 meters height in our sea conditions. Fig. 4 shows a time series of the ship's motions (roll, pitch and heave) on a vessel like the one to be used in the sea trials.

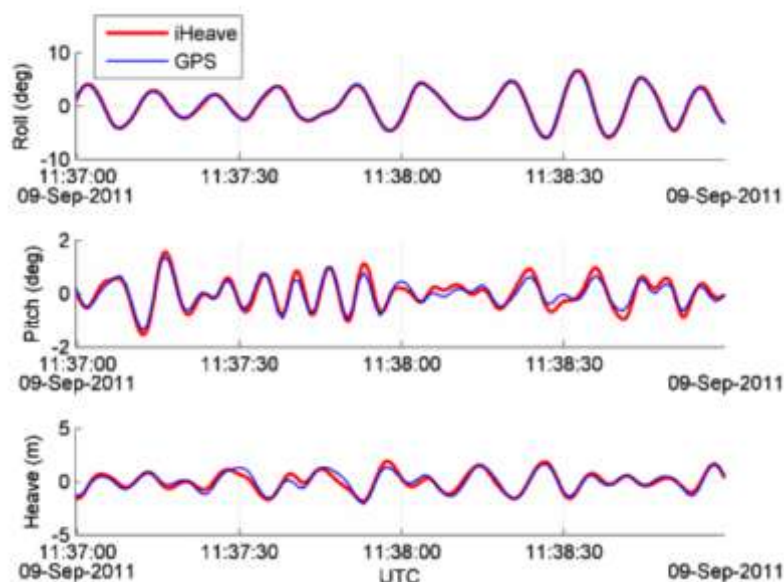


Fig. 4. Boat movement in "Measuring vessel motions using a rapid-deployment device on ships of opportunity."

From the data obtained, a roll angular velocity of 2 deg/sec and a heave acceleration of 0.5 m/s² are estimated. These movements will be used in the following sections to calculate the forces in the flywheel and evaluate all possible solutions.

3.2.3. EXTREME CONDITIONS

The extreme conditions or worst case should be delimited by regulations and governments, but there isn't any specific regulation for flywheel or similar machines onboard. The only limitation found in the regulation is with the classification societies with the following table.

Table 1. Regulation of angle of inclination for machinery and safety equipment on a boat.

Installations, components	Angle of inclination (degrees) (1) (4)			
	Athwartship		Fore and aft	
	static	dynamic	static	dynamic
Main and auxiliary machinery	15	22,5	5	7,5
Safety equipment, e.g. emergency power installations, emergency fire pumps and their devices	22,5(2)	22,5 (2)	10	10
Switch gear, electrical and electronic appliances (3) and remote control systems				
(1) Athwartship and fore-and-aft inclinations may occur simultaneously. (2) In ships for the carriage of liquefied gases and of chemicals the emergency power supply must also remain operable with the ship flooded to a final athwartship inclination up to a maximum of 30°. (3) No undesired switching operations or operational changes are to occur (4) Where the length of the ship exceeds 100m, the fore-and-aft static angle of inclination may be taken as 500/L degrees, where L is the length of the ship, in metres, as defined in Pt B, Ch 1, Sec 3, [2.1.1]				

According to the table, the flywheel must be designed for a maximum angle of inclination of 22.5 degrees. In "Offshore Application of the Flywheel Energy Storage" [3], a similar project with a worse case is presented, with a smaller boat and higher waves. This project presents their worst case with the following characteristics:

- Roll movement: +/- 45 deg in 12 sec
- Pitch movement: +/- 12 deg in 9 sec
- Heave acceleration: 0.4 g
- Surge acceleration: 0.25 g

3.3. MAIN TECHNICAL CHARACTERISTICS OF THE FINAL DEMONSTRATOR

The following table summarises the key technical specifications of the marinized KESS demonstrator developed within POSEIDON, alongside the equivalent parameters of the terrestrial version of the same system for reference. Table 2. summarises the differences between the prototype for land-based applications and the one developed as part of the POSEIDON project.

Table 2. Key technical specifications of the POSEIDON KESS demonstrator.

Parameter	Terrestrial	Marinized (POSEIDON)
Flywheel mass	400 kg	400 kg
Flywheel material	EN-GJS-1050-6 (cast iron)	EN-GJS-1050-6 (cast iron)
Operating speed range	9,000 – 13,000 rpm	8,000 – 10,400 rpm
Nominal power	24 kW	20 kW
Usable energy (operational window)	7.3 MJ (2.02 kWh)	3.97 MJ (1.10 kWh)
Total energy stored (from standstill to max speed)	15.2 MJ (4.22 kWh)	9.7 MJ (2.69 kWh)
Bearing configuration	2 hybrid ceramic ball bearings	4 hybrid ceramic ball bearings (double configuration)
Electric machine	6/4 SRM in vacuum	6/4 SRM in vacuum
Power converter	3-phase Asymmetric bridge converter, 750VDC	3-phase Asymmetric bridge converter, 750VDC
Target vacuum pressure	5 mbar	5 mbar
Bearing life at operational load	787 h (single config)	> 4,300 h (double config)
Maximum bearing radial load (extreme conditions)	21.5 kN	51 kN capacity (double config)
Overall dimensions	Ø598 × 382 mm	Ø700 × 382 mm (housing incl.)

3.4. COMPARISON WITH TERRESTRIAL BASELINE

The principal differences between the terrestrial and the marinized configurations arise from the need to accommodate the additional mechanical loads induced by ship

motion. Fig. 5 shows the previously manufactured KESS prototype (terrestrial) and the prototype built for the POSEIDON project. The key modifications introduced during the marinization process are summarised below:

- Operating speed range reduction: The maximum speed was reduced from 13,000 rpm to 10,400 rpm to keep all resonant frequencies of the rotodynamic system outside the operational range when the double bearing configuration is adopted. This reduction results in a decrease of the usable stored energy from 7.3 MJ to 3.97 MJ in the operational window, a trade-off accepted in favour of structural integrity and bearing life under marine conditions.
- Bearing configuration upgrade: The original two-bearing configuration was replaced by a four-bearing double configuration using ball bearing model 6207 at each end of the rotor shaft. This change was driven by the need to support the gyroscopic forces induced by vessel roll motion, which at operational speed and a representative roll angular velocity of 2 deg/s reach values approximately four times higher than the inertial forces alone. The double configuration raises the bearing limit load from 25.5 kN to 51 kN and extends the bearing life from 787 hours to more than 4,300 hours under operational loading.
- Flywheel material change: During the engineering design stage, an interface sliding problem was identified between the SRM rotor and the flywheel. This required the selection of a new flywheel material with modified thermal and mechanical compatibility properties, necessitating the construction of a dedicated test bench for thermal characterisation.
- Orientation selection: The vertical flywheel orientation was selected as the most appropriate for the targeted ferry application, as it minimises the gyroscopic torque contribution from the dominant roll motion while keeping the bearing load from weight in the axial direction, where the bearings are better suited to sustain it.

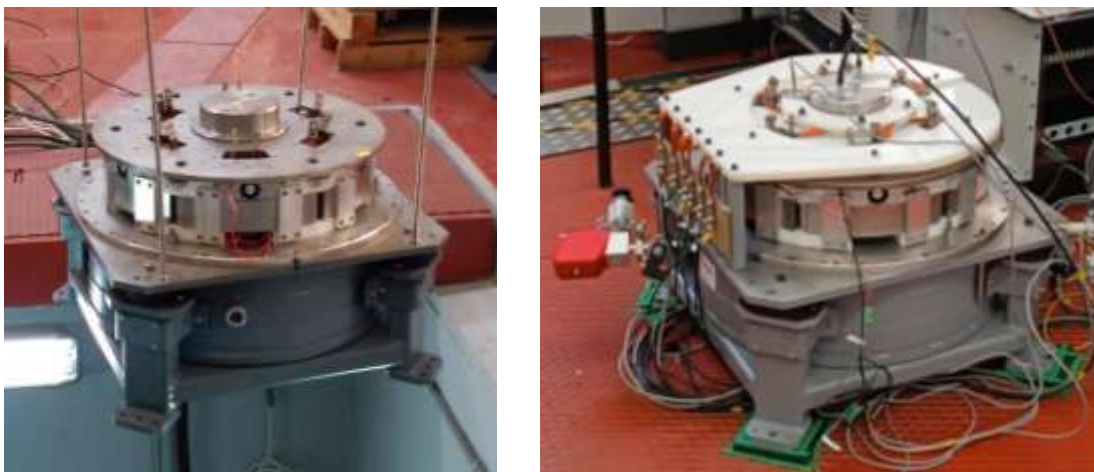


Fig. 5 KESS prototype for land-based applications (left) and the marine-adapted KESS prototype for the POSEIDON project (right).

4. MAIN TECHNICAL RESULTS ACHIEVED

The results achieved in WP3 demonstrate that POSEIDON has moved the marine KESS concept from design definition to integrated experimental validation under relevant laboratory conditions. The value of these results does not lie only in the fabrication of a prototype, but in the delivery of technical assets that can be exploited in future marine storage products and integration studies. These assets include the marinated system architecture, the rotodynamic design rules, the machine–converter–control integration, the safety-oriented design measures and the controlled-motion validation route developed for ship-motion assessment. Together, these results strengthen the technical basis for future onboard deployment of fast-response non-battery storage solutions in support of more efficient and lower-emission waterborne transport.

4.1. ACHIEVEMENT 1: SUCCESSFUL MARINIZATION OF A SLOW-FLYWHEEL CONCEPT

The first major achievement of WP3 is the successful conversion of a terrestrial KESS concept into a marinated demonstrator specifically adapted to the motion and integration constraints of waterborne transport. This is explicitly reflected in the change from the terrestrial reference values reported in D3.2 — 9, 000 rpm to 13, 000 rpm operating range, 22 kW nominal power and 7.3 MJ usable energy — to the marinated POSEIDON prototype configured for 8, 000 rpm to 10, 400 rpm, 20 kW nominal power and 3.97 MJ usable energy, demonstrating that marine adaptation was not a cosmetic modification but a substantive redesign to accommodate ship-motion loads and reliability constraints.

This marinated architecture is a Key Exploitable Result because it provides a documented engineering basis for future flywheel products intended for ferries and other hybrid vessels. From a Horizon Europe perspective, this result contributes to broadening the portfolio of fit-for-purpose non-battery energy storage solutions for climate-neutral waterborne transport. It is therefore relevant not only as a prototype achievement, but also as a reusable engineering reference for future industrialisation, integration and regulatory dialogue.

4.2. ACHIEVEMENT 2: DECOUPLED POWER AND ENERGY DESIGN ALIGNED WITH MARINE USE

The second major result is the demonstration of a flywheel architecture in which energy and power are structurally decoupled through the combination of a dedicated rotating mass and a switched reluctance machine. In practical terms, this means that the KESS is designed for high power density over short operating windows rather than for long-duration energy supply. This characteristic makes the technology suitable for short duty cycles and frequent charge/discharge cycles in marine hybrid systems rather than long-duration autonomy [4].

Such an operating profile is relevant for onboard functions including peak shaving, load levelling, grid frequency stabilization and the management of fast power transients linked to manoeuvring or variable auxiliary demand. The WP3 evidence supports this positioning at the level of architecture and integrated operation, although final nominal-vacuum performance mapping remains pending. For that reason, the public claim should be that POSEIDON has demonstrated the technical relevance of the KESS for fast-response marine services, not yet its fully optimised final performance envelope.

4.3. ACHIEVEMENT 3: ROBUST MACHINE-CONVERTER-CONTROL INTEGRATION

A further key result of WP3 is the successful integration of the switched reluctance machine, the dedicated bidirectional converter and the supervisory control environment into a single experimental system. The laboratory campaign demonstrated supervised start-up, acceleration, speed holding, inertial running and controlled braking, thereby confirming that the main electrical and control subsystems can operate coherently as an integrated KESS demonstrator. The optimisation of speed- and current-dependent turn-on and turn-off firing angles constitutes an additional exploitable result because it provides validated control logic for future marine flywheel implementations [4].

This result is important beyond the prototype. The validated machine-converter-control chain provides a reference for the integration of flywheel storage into shipboard power management architectures, including communication, supervision and protection functions. In exploitation terms, this reduces technical uncertainty for future scaling, system integration and interaction with hybrid marine electrical networks [5].

4.4. ACHIEVEMENT 4: ROTODYNAMIC AND BEARING DESIGN FOR MARINE SERVICE AND MANUFACTURING

The rotodynamic and bearing design developed in WP3 constitutes one of the most relevant engineering results of the project. The analyses performed in D3.1 showed that ship-motion-induced gyroscopic loads are a dominant design driver for marine flywheel systems and that the original single-bearing approach did not provide an acceptable lifetime under the selected marine operating conditions. The final double-bearing configuration increased load capacity to 51 kN, extended expected bearing life beyond 4,300 h and shifted critical speeds outside the selected operating range of 8,000–10,400 rpm.

This result should be presented as both a hardware outcome and a design methodology outcome. The bearing sizing logic, the marine load assumptions and the rotodynamic validation route form a reusable engineering framework for future marine flywheel developments. In a public Horizon Europe report, this is an important Key Exploitable Result because it reduces one of the main barriers to flywheel adoption in waterborne environments: the credible management of gyroscopic and motion-induced mechanical loads.

4.5. ACHIEVEMENT 5: EXPERIMENTALLY SUPPORTED MARINE-MOTION ASSESSMENT

One of the most distinctive outcomes of WP3 is the development and execution of a controlled-motion validation route for the marine KESS at CEHIPAR. The demonstrator was mounted on an oscillating hexapod through four six-component dynamometers and subjected to vertical motion, rotation around the X axis and rotation around an axis at 45 degrees in the XY plane. This campaign generated traceable datasets on realised motion, centre-of-gravity response and force and moment transmission under representative marine-like excitation.

This result matters because marine motion was identified from the outset as one of the main barriers to the deployment of flywheel systems onboard vessels. The project therefore did not stop at standard bench validation but established an experimentally supported methodology to assess motion-induced loading in a controlled environment. Even though the deliverable does not publish a complete quantitative reduction of every load peak and phase relationship, the demonstrated capability to instrument, execute

and document these tests is itself a major exploitable result and a likely enabler for future certification-oriented testing. Fig. 6 shows an image of the KESS at the CEHIPAR facilities.

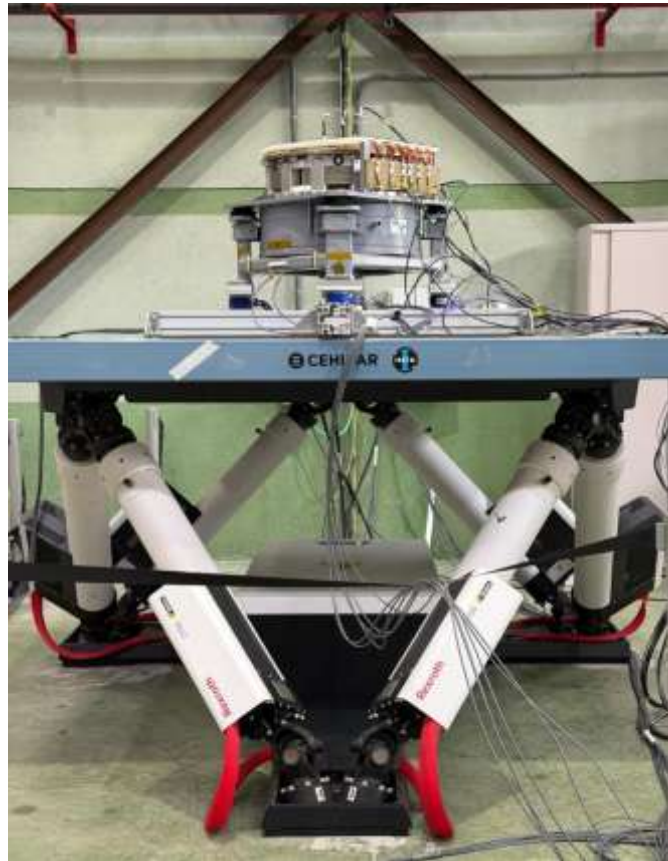


Fig. 6 KESS on an oscillating platform where the tests have been carried out at CEHIPAR.

4.6. PERFORMANCE INTERPRETATION AND REFERENCE METRICS

The public interpretation of KESS performance must distinguish clearly between design values, demonstrated operating evidence and pending optimisation. The traceable values currently supported by the WP3 documentation are an operating speed range of 8,000–10,400 rpm, nominal power of 20 kW, total stored energy of 9.7 MJ and usable operating energy of 3.97 MJ. These values place the demonstrator in a technically relevant range for fast-response support in marine hybrid systems, where short-duration power exchange is more important than long energy autonomy.

However, D3.4 also states that the reported laboratory campaign was carried out at atmospheric pressure because operation at the target vacuum level of 5 mbar was prevented by a sleeve-related issue. Consequently, the present deliverable should not claim final round-trip efficiency, standby-loss performance or definitive thermal behaviour under nominal vacuum conditions. The defensible public statement is that POSEIDON has validated the functional integration and motion-response framework of a marinized KESS demonstrator and has established the technical basis for further optimisation towards nominal operating conditions.

5. SAFETY INTEGRATION AND RISK ASSESSMENT RESULTS

5.1. SAFETY AS A PROJECT REQUIREMENT

Safety was not treated in POSEIDON as a posterior verification exercise but as a transversal project objective. The Grant Agreement explicitly defines one of the project-specific objectives as the determination of safety issues, potential long-term risks and regulatory solutions for the three ESS technologies, and WP6 was created specifically to address regulation review, hazard identification and complete risk assessment through a systems-engineering approach aimed at eliminating hazards where possible and minimizing residual risks where elimination is not possible.

For the KESS, this safety logic was already embedded in the WP3 design process. D3.1 incorporated marine extreme conditions into the rotodynamic calculation, D3.2 translated critical findings into material and interface redesign, D3.3 verified mechanical assembly integrity, insulation and vacuum-related aspects, and D3.4 extended validation to motion-induced loads under controlled oscillation, all of which are design and test actions directly connected to intrinsic safety and risk reduction [6].

5.2. MAIN HAZARDS RELEVANT TO THE KESS

Based on the KESS design and test documentation, the principal hazards for a marine flywheel demonstrator can be grouped into mechanical, vacuum, electrical, thermal, control and integration-related categories. The most relevant mechanical hazards are rotor/flywheel structural failure, overspeed, excessive vibration, bearing overload or premature degradation, loss of dynamic balance and excessive gyroscopic load transfer under vessel motion.

Vacuum-related hazards include loss of vacuum, abnormal aerodynamic heating and degradation of performance associated with enclosure leakage or sleeve-related failure modes. Electrical and control hazards include overcurrent, DC-link overvoltage, converter faults, loss of control synchronization, sensor failure, unintended torque generation and unsafe state transitions in the presence of alarms or interlock failures.

At system-integration level, marine deployment also introduces hazards linked to humidity, salinity, shock, vibration, restricted installation spaces and interaction with the ship electrical network. These concerns are consistent with the Grant Agreement description of WP6 risk assessment and with the earlier Danish Maritime Fund experience, where shock, vibration, EMI and large motion excursions were explicitly treated as fundamental boundary conditions for marine flywheel use.

5.3. DESIGN MEASURES THAT REDUCED RISK

Several of the most important risk-reduction measures can be directly traced in the WP3 documentation. First, the design was intentionally shifted toward a slow-flywheel concept rather than a very-high-speed alternative, thereby reducing the dependence on more delicate high-speed subsystems and improving structural robustness under marine loading.

Second, the bearing and rotodynamic design was repeatedly refined to cope with motion-induced loads. The adoption of the double-bearing configuration, the detailed Campbell-diagram analysis, the verification of critical speeds outside the operating range and the inclusion of radial dampers and magnetic-load-relief elements all act as preventive measures against resonance, overload and excessive wear under marine operation.

Third, the thermal-mechanical redesign of the flywheel-rotor interface addressed a latent hazard that could otherwise have compromised torque transmission and mechanical integrity at elevated temperatures. The material changes toward EN-GJS-1050-6 and the revised contact concept therefore represent not only an engineering optimization but also a concrete risk-mitigation action derived from test evidence.

Fourth, the electrical subsystem was designed with explicit protective and supervisory functions. D3.2 and D3.3 report protections against overcurrent and short circuit in AC and DC paths, monitored current and voltage channels, bearing and coil temperature monitoring, speed measurement, emergency stop functions, alarm handling and controlled communication with the high-level controller, all of which contribute to fault detection and safe state management [7].

Finally, the laboratory validation approach itself is part of the safety strategy. By progressively moving from subsystem FAT to integrated laboratory tests and then to controlled-motion experiments, the project reduced uncertainty before any future onboard deployment. This staged validation route is fully consistent with the systems-engineering philosophy described for WP6 in the Grant Agreement.

5.4. HIGH-LEVEL SUMMARY LINKED TO D6.3 RISK ASSESSMENT

The attached spreadsheet D6.3 is identified in the Grant Agreement as the WP6 “Risk Assessment” deliverable for FRESS technologies, developed to provide a complete assessment focused on the storage systems and the electrical network where they are implemented.

At high level, the KESS evidence in WP3 supports the conclusion that the demonstrator was developed under an intrinsically safer design philosophy, in which major hazards were either reduced through architecture choices or controlled by dedicated safeguards. In particular, structural and motion-induced hazards were addressed through conservative rotodynamic design and controlled-motion testing; interface and integrity hazards were reduced through targeted material and assembly redesign; and electrical/control hazards were mitigated through converter protections, interlocks, monitored variables and supervised start-up and shutdown procedures.

Because the detailed hazard register, risk ranking, action status and residual-risk scoring are contained in the D6.3 file, the public D3.5 should summarize those results without reproducing confidential or excessively granular engineering details (see Table 3). A suitable public interpretation is that the KESS demonstrator has been developed with safety-by-design criteria, that the principal mechanical and electrical hazards have been identified and addressed through design measures and testing, and that the resulting residual risks have been progressively reduced to a level compatible with further development toward higher TRL and future onboard integration, subject to the completion of the remaining optimization steps and regulatory pathway.

Table 3. Summary of identified hazards for the KESS.

ID	Hazard	Root-Cause	Domain
H1	Flywheel structural failure (burst)	Fatigue crack growth due to stress concentration; material defect; overspeed event beyond design limit	Rotating mechanical
H2	Overspeed event	Control system failure; power converter malfunction; loss of speed feedback signal	Rotating mechanical / Electrical

H3	Bearing failure	Exceeding load or speed limits; lubricant degradation; inadequate maintenance interval	Rotating mechanical
H4	Vacuum enclosure failure	Structural fatigue of vacuum sleeve; seal degradation; impact from external loads; sleeve-rotor contact	Vacuum system
H5	Loss of vacuum integrity	Vacuum pump failure; leak at sealing elements; damage to enclosure	Vacuum system
H6	Electrical fault in power converter	Short circuit in IGBT switches; insulation failure; DC-link overvoltage	Electrical
H7	Stator coil overtemperature	Insufficient cooling; excessive current; loss of vacuum (increased aerodynamic losses)	Electrical / Thermal
H8	Gyroscopic load exceedance	Operation in sea conditions beyond the design envelope; loss of vessel motion monitoring	Marine / Structural
H9	Uncontrolled energy release during braking	Grid disconnection during charging; failure of braking resistor or discharge path	Electrical / Safety
H10	Toxic / hazardous material release	Wear debris from bearings or rotor; oil contamination from vacuum pump	Environmental

5.5. MITIGATION MEASURES AND ACTIONS TAKEN

For each hazard classified as HIGH or MEDIUM, design-embedded mitigation measures were defined and incorporated into the KESS demonstrator. The principal measures are described below:

H1 – Flywheel burst

Mitigation: The flywheel was dimensioned with a safety margin of 30% on the maximum allowable stress, as established in D3.1. The maximum operating speed is enforced by the control system with a hard overspeed limit, and the flywheel is enclosed in a containment housing designed to arrest debris in the event of a fracture. The flywheel material (EN-GJS-1050-6) was selected for its ductile failure mode, avoiding brittle fragmentation. Dynamic balancing is required per ISO 11342 to limit inertial bearing loads.

H2 – Overspeed

Mitigation: Two independent overspeed protection layers are implemented: a software limit enforced by the DSP controller, and a hardware overcurrent interlock on the power converter that prevents motoring torque above the maximum speed setpoint. The absolute encoder provides redundant speed feedback. A dedicated overspeed test was performed during FAT to verify both protection layers.

H4 – Vacuum sleeve failure

Mitigation: The vacuum sleeve failure experienced during the laboratory campaign was identified as a contact event between the rotating part of the electric machine and the sleeve inner surface, occurring at sub-nominal vacuum pressure. A repair programme was implemented, and additional clearance verification steps were added to the commissioning procedure. In the worst case where full vacuum cannot be restored, operation at 5,000 rpm (the speed at which the demonstrator will operate on board the vessel) can be maintained without vacuum, as confirmed by the operating experience during the CIEMAT tests.

H6 – Electrical fault in power converter

Mitigation: The converter includes IGBT gate-drive protection (desaturation detection), DC-link overvoltage protection with dump resistor, phase overcurrent protection, and thermal interlocks on all semiconductor modules. All protection functions were verified during the converter FAT. The power converter is physically segregated from the high-voltage DC bus by isolation contactors that open on any major alarm condition.

H8 – Gyroscopic load exceedance

Mitigation: The double bearing configuration was specifically designed to sustain the loads corresponding to the extreme sea conditions defined in D3.1, including the reference roll rate of 23.5 deg/s ($\pm 45^\circ$ in 12 seconds). The bearing limit load of 51 kN in the double configuration provides a margin factor of more than 2.3 over the maximum calculated radial force of 21.5 kN. In addition, an operational procedure was defined to reduce or stop the flywheel if sea conditions exceed the design envelope.

6. VALIDATION AND TEST EVIDENCE

6.1. VALIDATION LOGIC ACROSS D3.3 AND D3.4

The validation of the POSEIDON KESS followed a staged approach. First, D3.3 documented the fabrication status and Factory Acceptance Tests of the mechanical and power-converter subsystems; second, D3.4 documented the integrated laboratory testing of the complete demonstrator at CIEMAT; and third, the same deliverable incorporated a dedicated campaign under controlled oscillatory motion at CEHIPAR.

This sequence is technically sound for a marine flywheel system because it separates manufacturability verification, functional integration and marine-motion assessment. It also matches the testing intentions already set out in the Grant Agreement for Task 3.3, which explicitly mentioned torque characterization, friction, heating, overspeed, vibration and operation under controlled oscillation on a moving table.

6.2. MAIN LABORATORY RESULTS AT CIEMAT

The CIEMAT laboratory campaign demonstrated that the complete KESS assembly could be operated in a controlled and instrumented environment. D3.4 reports the availability of phase-current measurement, DC-link voltage, rotor position and speed, optical temperature sensors for rotor/flywheel, PT100 sensors for coils and bearings, dedicated LABVIEW supervision interfaces and SbRIO-based high-level control for integrated tests.

The executed test set included acceleration from standstill or low speed to 1000 rpm and 3000 rpm, speed holding around 1000 rpm and 3000 rpm, inertial running and variable-current braking. Across these tests, D3.4 reports coherent relationships between speed, acceleration, machine current and firing-angle schedules, thereby validating the practical operation of the machine-converter-control chain.

A relevant limitation is also documented with transparency: due to an issue in the flywheel sleeve, the demonstrator was tested at atmospheric pressure instead of the target 5 mbar vacuum condition. This means that the achieved results should be interpreted primarily as system-operation and integration validation, while the final nominal performance under vacuum remains to be completed in a subsequent optimization phase [8].

6.3. CONTROLLED-MOTION TESTS AT CEHIPAR

The CEHIPAR campaign extended the validation beyond conventional bench testing. The KESS was mounted on an oscillating hexapod through four six-component dynamometers, and tests were executed for vertical motion along the Z axis, rotation around the X axis and rotation around an axis at 45 degrees in the XY plane, with several combinations of flywheel rotational speed, oscillation frequency and rotation sense.

The campaign confirmed that the selected setup could reproduce the defined motion cases and even extending the envelope to higher speeds and higher oscillation frequencies after the first runs confirmed sufficient operating margin. It also produced processed datasets describing realised motion, centre-of-gravity response and force/moment transmission through the support points under representative marine-like excitation.

From a validation standpoint, this is one of the strongest achievements of the project because it provides laboratory evidence for the very phenomenon that motivated much of the marinization work: the influence of vessel motion and gyroscopic loading on the flywheel system. Even without a complete published quantitative reduction of every test

file, the demonstrated ability to instrument, execute and document those motion tests is a substantial result.

6.4. LESSONS LEARNED

The following lessons learned are identified from the WP3 development cycle and are considered relevant for future developments of marine flywheel technology at higher TRL stages:

- **Rotor-flywheel interface compatibility:** The interference-fit interface between the SRM rotor and the flywheel requires careful assessment of differential thermal expansion across the full operational temperature range, particularly when the two components are made of different materials. The construction of a dedicated thermal characterisation test bench at an early stage of the engineering design phase is recommended for future developments of similar systems.
- **Vacuum system robustness:** The vacuum sleeve is a critical element for the energy efficiency of the KESS, since aerodynamic losses at atmospheric pressure are substantially higher than at the target 5 mbar. Robust qualification procedures for the vacuum sleeve, including contact clearance verification and pressure cycling tests, should be incorporated into the FAT protocol for future demonstrators.
- **Bearing life under marine loading:** The analytical bearing life calculations based on the gyroscopic load model developed in D3.1 were validated by the CEHIPAR test results, confirming the design approach. The methodology developed for the POSEIDON KESS provides a reusable framework for sizing bearings of marine flywheel systems in future applications.
- **Controlled-motion testing as a certification enabler:** The CEHIPAR hexapod campaign demonstrated that controlled oscillatory motion testing provides experimentally traceable evidence of the KESS response under marine-representative loads. This type of test is likely to be required by classification societies as part of the approval process for flywheel energy storage systems on board vessels, and early engagement with the relevant class society (Bureau Veritas in the POSEIDON case) is recommended for future projects.
- **High-Level Control architecture:** The integration of the KESS within a multi-storage supervisory architecture through CAN communication was successfully demonstrated during the integrated CIEMAT tests. The SbRIO-based HLC platform and the associated communication protocol provide a validated reference implementation for the integration of flywheel storage into shipboard power management systems. Based on the WP3 evidence, the public conclusion that can be robustly supported is that the POSEIDON KESS reached the level of an integrated laboratory demonstrator with successful supervised operation and motion-response testing under relevant laboratory conditions. The available evidence confirms functional readiness of the demonstrator architecture, suitability of the adopted control strategy, manufacturability of the main subassemblies and a credible basis for further performance optimization and future marine integration.

6.5. TRL ASSESSMENT

The Technology Readiness Level of the POSEIDON KESS was assessed at the beginning of the project as TRL 4 (technology validated in laboratory), based on the existing CIEMAT experience with slow flywheel technology for energy management applications. The development activities carried out within WP3 were designed to advance the system to

TRL 6 (technology demonstrated in a relevant environment). The following table summarises the TRL progression achieved through the WP3 deliverable sequence:

Table 4. TRL progression achieved within WP3.

TRL	Evidence	Achieved in POSEIDON
TRL 4	Technology validated in laboratory environment	Entry state; confirmed by CIEMAT terrestrial flywheel heritage and D3.1 design analysis
TRL 5	Technology validated in industrial relevant environment	Achieved through D3.2 (engineering design incorporating marine constraints) and D3.3 (FAT on full demonstrator)
TRL 6	Technology demonstrated in relevant environment	Substantially achieved through D3.4: functional laboratory validation at CIEMAT and CEHIPAR motion testing

7. CONCLUSIONS AND NEXT STEPS

The work carried out in WP3 demonstrates that the POSEIDON consortium has successfully designed, engineered, fabricated and laboratory-validated a marinized kinetic energy storage system based on a slow flywheel for marine applications. The resulting demonstrator integrates a flywheel, switched reluctance machine, bidirectional converter, vacuum enclosure, bearing system, instrumentation, supervision environment and high-level control architecture into a coherent experimental module for fast-response onboard energy-storage functions.

The main conclusions drawn from the work reported in D3.5 are the following:

- A marinized KESS demonstrator was successfully developed, manufactured and tested within the POSEIDON project, based on a slow-flywheel concept with a 400 kg rotating mass coupled to a 6/4 Switched Reluctance Machine operating in vacuum. The final configuration adopts a double-bearing arrangement (4 hybrid ceramic ball bearings, model 6207) and an operating speed range of 8,000–10,400 rpm, with a usable stored energy of 3.97 MJ and a nominal power of 20 kW.
- The marinization strategy developed in D3.1 was validated both analytically and experimentally. The rotodynamic analysis confirmed that the double-bearing configuration places all critical speeds outside the operational range, while the CEHIPAR controlled-motion campaign provided experimental evidence that the load levels experienced under marine-representative oscillatory conditions are consistent with the design predictions.
- The Factory Acceptance Tests reported in D3.3 were completed satisfactorily, demonstrating the conformity of the fabricated demonstrator with the design requirements for all main subsystems.
- The laboratory validation campaign at CIEMAT confirmed the functional integrity of the complete integrated KESS system, including the correct operation of the SRM controller with speed- and current-dependent firing angle schedules, the bidirectional power exchange capability of the converter, and the feasibility of coordinated supervisory operation within a multi-storage architecture.
- The controlled-motion campaign at CEHIPAR, comprising fifteen test cases covering vertical, rotational and combined oscillatory excitations at flywheel speeds of 0, 1,000 and 3,000 rpm, demonstrated that the KESS responds to marine-representative motions in a manner consistent with the design predictions, confirming the adequacy of the selected bearing configuration and structural mounting for the target operational profile.
- The risk assessment conducted in D6.3 and summarised in this deliverable confirmed that the KESS was designed with safety as an intrinsic requirement.

From a project perspective, these outcomes fulfil the intent of D3.5 as defined in the Grant Agreement, namely, to report the main technical achievements of the KESS applied in the naval sector. They also contribute directly to the broader POSEIDON objective of demonstrating innovative fast-response energy storage systems for waterborne transport with attention to efficiency, safety and onboard applicability.

The results achieved in WP3 establish a solid technical foundation for the continuation of the POSEIDON project towards its on-board demonstration objectives. The next steps planned in the project roadmap include:

- Integration of the KESS with the grid converter and full-scale multi-storage tests in the laboratory configuration (May–June 2026).

- Site Acceptance Tests on board the BALEARIA ferry (planned for November 2026), constituting the TRL 7 demonstration milestone of the project. Results of the onboard integration and performance will be included in D5.6.
- Formal classification society review process with Bureau Veritas, based on the design documentation and test evidence accumulated through D3.1–D3.5.
- In the medium term, the POSEIDON KESS architecture provides a replicable modular building block for fast-response energy storage in a range of maritime applications, from passenger ferries to offshore service vessels, with potential for capacity scaling through parallel connection of multiple modules.

The POSEIDON KESS demonstrator constitutes a credible and technically relevant step toward the adoption of flywheel-based fast-response storage in naval and waterborne applications. Compared with earlier marine flywheel references focused primarily on simulation and concept validation, POSEIDON advances the state of development by delivering a documented marinized demonstrator, a validated control-and-converter chain, and an experimental motion-testing framework specifically targeted to the real constraints of marine service.

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