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Executive summary

The present deliverable releases the results regarding the novel dual-Hardware-In-the-Loop (Dual HIL) approach, methodologies and metrics proposed in the IMPACT project. It does so in order to facilitate their implementation in future testing practices for the development of wave energy technologies. Section 2 provides an overview of the IMPACT project, including its structure, implementation, motivation, project partners and objectives.

The definition of the test rig parameters and mechanical specifications is intrinsically linked with a detailed understanding of the loading environment that a Wave Energy Converter (WEC) will be subject to during its lifetime. In the initial phase of the IMPACT project, four research areas - mechanical/structural, electrical, techno-economic and environmental – were addressed in parallel to inform the baseline test rigs developments, namely their requirements and specifications. In Section 3, the definition of a WEC database to characterize the parameters of different WEC types and modes of operation is described, from which was made a selection of WEC target deployment sites and relevant environmental conditions, in order to characterize the range of environmental conditions that WECs can be exposed to. This was followed by the creation of numerical models for the selected WECs to simulate various design situations and define the mechanical specifications for the test rigs needed to satisfy the combination of WEC types. Section 3 compiles the test rigs specifications and discusses associated limitations and assumptions.

The demonstration of survivability and reliability are at the core of WEC design and underpin the success of a future wave energy industry. Section 4 identifies testing methodologies and metrics that support the development of WECs, specifically under three evaluation areas: performance, reliability, and survivability. The proposed novel testing framework aims at ensuring the survival of a WEC over the full range of Design Load Conditions and demonstrating its reliability for the duration of its design life. The critical aim here was to accelerate technology development and provide test-based inputs to key design drivers, leading to shorter development pathways to the market. Specifically: a) the rigs specifications were harmonized to be made compliant with different testing approaches; b) a methodology for the accelerated testing of WEC design situations to demonstrate the survivability and reliability of a WEC was defined; and c) several novel metrics to demonstrate the survivability and reliability of a WEC and its key subsystems were defined.

Based on input data from the project, the Dual HIL testing platform was designed and activities were divided into: a) designing, manufacturing, assembling of the drivetrain test rig; b) designing, manufacturing, assembling of the structural components test rig; c) execution of the acceptance tests of the two test rigs; d) integration of the two Hardware-In-the-Loop (HIL) test rigs to develop the Dual HIL testing platform. Section 5 describes the design of the test rigs and the Dual HIL platform. Namely the architecture, testing capabilities, final specifications, the assembly of the units, and the Internet-of-Things (IoT) framework including digital twins of the rigs and Device-Under-Test (DUT) for monitoring and analysing the key test results.

Section 6 provides an overall description of the tests carried out in the project with the rigs and discusses the applicability of the novel testing methodology. It includes a brief explanation of the selection process for the case studies and the approach for test and risk management. It summarises the testing campaign management activity, which aimed to select candidate devices for testing on the IMPACT rigs and manage the corresponding testing campaigns. In particular, it addresses the relevant test procedures and documentation, including applicable details related to the planning, execution and post-test phases, i.e. pre-processing, processing and post-processing considerations. In fact, the completion of both HIL and Dual HIL tests in the IMPACT rigs can be seen as a demonstration of their capabilities, bringing new a new testing approach to the ocean energy sector.

Finally, Section 7 lists several key conclusions about the project, focusing on further recommendations for using the IMPACT testing platform after the end of the project and for establishing Dual HIL as a best practice to accelerate the development pathway of the ocean energy technologies.

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1 Introduction

1.1 Purpose

The European Commission (EC) INEA (Innovation and Networks Executive Agency) has awarded the IMPACT (Innovative Methods for wave energy Pathways Acceleration through novel Criteria and Test rigs) project to VGA srl, under Grant Agreement (GA) Number 101007071. The IMPACT project aims to design and manufacture two novel test rigs covering 75% of Wave Energy Converter (WEC) sub-systems affecting the device Levelised Cost Of Energy (LCOE). The innovative dual Hardware-In-the-Loop (Dual HIL) testing platform, novel test criteria and metrics aim to increase WEC reliability and reduce testing time by 50%.

The project brings together VGA srl, an engineering company specializing in the design and development of test platforms and prototypes, an independent marine renewables engineering consultancy (Yavin Four Consultants, Y4C), electrical power system experts (SINTEF Energy Research, SER), experts in maritime technology (SINTEF Ocean, SOCEAN) and leading socio-economic and environmental impact researchers (University College Cork – Marei, UCC), to complete a range of desktop, numerical and experimental activities related to the design, development, fabrication and testing of a novel Dual HIL testing platform.

This report summarizes the key findings of the project and how they together form a set of innovative approaches for rig testing in wave energy. Specifically, it details how the project, beginning with an understanding of the loading environment a WEC will encounter throughout its lifespan, culminated in the demonstration of the ability of a new set of dry-test rigs to perform tests on WEC componentry. These tests target performance, reliability and survivability studies following a novel test methodology framework established in the project and using different approaches, including HIL and Dual HIL.

1.2 Scope

The report is organized into eight sections. Following this introduction:

- Section 2 provides an overview of the IMPACT project, including its structure, implementation, motivation, and objectives.
- Section 3 compiles the test rigs specifications and discusses associated limitations and assumptions.
- Section 4 details the IMPACT testing methodologies, reviews existing metrics, and proposes novel metrics within three evaluation areas: performance, reliability, and survivability of WECs.
- Section 5 describes the design of the test rigs and the Dual HIL. Namely the architecture, testing capabilities, final specifications, the assembly of the units, and the IoT framework including digital twins of the rigs and / or the DUT for monitoring and analysing their loads.
- Section 6 provides an overall description of the tests carried out in the project with the rigs and discusses the applicability of novel testing methodologies. It includes a brief explanation of the selection process for the case studies and the approach for test and risk management. The test setup, test execution and examples of results and post-processing are shown for the test demonstration campaigns performed.
- Section 7 lists several key conclusions about the project, focusing on further recommendations for using the IMPACT testing platform after the end of the project and for establishing Dual HIL as a best practice to accelerate the development pathway of the ocean energy technologies.
- Section 8 describes how to access IMPACT publications and other sources.

1.3 Abbreviations and Acronyms

CAPEX	Capital Expenditure
CBOS	Cyclic Bend Over Sheave
CM	Condition Monitoring
CMS	Component Mode Analysis
CO	Frequency-based Control Optimality
CSP	Control Spectral Performance
DAQ	Data Acquisition
DEL	Damage Equivalent Load
DLC	Design Load Case
Dual HIL	Dual Hardware-In-the-Loop
DOF	Degree of Freedom
DT	Digital Twin
DUT	Device Under Test
EC	European Commission
EIA	Environmental Impact Assessments
ESS	Energy Storage System
FE / FEM	Finite Element / Finite Element Model
FEA	Finite Element Analysis
FLS	Fatigue Limit States
FMECA	Failure Mode, Effects and Criticality Analysis
FMU	Functional Mockup Unit
HIL	Hardware-in-the-loop
HMI	Human-Machine Interface
HPU	Hydraulic Power Unit
IoT	Internet of Things
LCOE	Levelized Cost Of Energy
MAEP	Mean Annual Energy Production
MRE	Marine Renewable Energy
O&M	Operation and Maintenance
OPEX	Operating Expenditure
OREDA	Offshore and onshore REliability DAta
OV	Output Variability
OVC	Output Variability Curve
PTO	Power Take-Off
RMS	Root Mean Square
ROM	Reduced Order Model
RT	Real Time
SER	SINTEF Energy Research
SHM	Structural Health Monitoring
SOCEAN	SINTEF Ocean
TAB	Technical Advisory Board
TPL	Technology Performance Level
TRL	Technology Readiness Level
UCC	University College Cork
UDP	User Datagram Protocol
ULS	Ultimate Limit States
ULS	Ultimate Limit State
WEC	Wave Energy Converter
WP	Work Package
Y4C	Yavin Four Consultants

2 The IMPACT project

2.1 Accelerating the development of WEC devices

Wave Energy Converter design and development is a complex subject due to the various aspects to be considered: devices can be subject to abnormal load on the power conversion chain during unexpected conditions that can overstress the mechanical components. State-of-the-art Power Take Offs (PTOs) are often inefficient when working outside design conditions and prone to failure. Other subsystems such as the control system, power management and moorings are deemed to be critical in terms of reliability: their failure may cause damage and serious consequences on the overall device operation.

The current development approach for WEC technologies usually sees all these subsystems tested in isolation at different scales and various levels of technology maturity due to testing restrictions, economic and time constraints. Techno-economical aspects, optimization and control functions are often considered as consecutive independent phases, while in reality they are interlinked.

The Joint Research Centre of the European Commission (EC) identified cost reduction and reliability as the main challenges for the wave energy sector. Given the high costs of device installation and the limited accessibility to the deployment site due to harsh weather, reliability is key to achieve competitive electricity costs. In particular, the EU recognizes the need of component and service standardization at early stages of development [1]. The demonstration of systems operation during their evolution from the computer to the lab and from the lab to the sea requires the accumulation of short- and long-term operational data. Performance, components, subsystems and system reliability, alongside O&M needs, are required inputs for design optimization and cost savings.

When targeting substantial, potentially dominant, optimization and cost reduction, the categories that most contribute to the overall WEC techno-economic viability are of particular interest. Overall, the main structure and Power Take-Off system are widely recognized as the main contributors to the LCOE [2] and devices' Capital Expenditure (CAPEX) [3].

The design, production and demonstration of a testing platform addressing the key subsystems of all the WEC types and standardized testing procedures, carried out in IMPACT as its main objective, is therefore instrumental in accelerating the development of WEC devices, reduce the technology costs and meet the goals of the EC.

2.2 The Dual Hardware-In-The-Loop testing

The platform developed in IMPACT implements the concept of the Dual HIL testing scheme.

The Technology Readiness Level (TRL) progress of a WEC finds its major bottleneck in the transition from wave tank tests (laboratory environment) to sea trials (operational environment) [4]. The most common approach of mixing scaled tank and rig testing does not always address critical points for the development of single components or subsystems in a holistic device point of view. These criticalities are exacerbated when the limitations introduced by multiple scales are considered: tank tests are typically performed under controlled conditions, on small-scale devices (1:15 to 1:60, indicatively) which do not include some subsystems (e.g. no power converter) or do not allow integration of the replicas of the real system (e.g. linear PTO simulated by an alternative, simplified damping system). Numerical models calibrated according to the tank test results may miss the key behaviours of larger scale systems, especially for the prediction of key components or subsystems working in critical conditions (e.g. survival mode, maximum power production, abnormal loading).

On the other hand, sea trials are performed in an uncontrolled environment, characterized by a complex loading pattern, on medium to large-scale prototypes (1:1 to 1:4, indicatively) which require fully functioning subsystems. Being uncontrolled, the environmental inputs may not match the (scaled) loading patterns for which the systems were designed for, which can significantly affect the value of the sea trials from an engineering design perspective. In addition, sea trials are most often capital-intensive activities, as they involve fabricating, commissioning and operating a complex system (the WEC) which may require the use of expensive equipment and vessels. To avoid high financial risks while enabling to increase the maturity of its technology, a rigorous TRL progress towards sea trials must involve prior validation and demonstration in a relevant environment [5]. Very often the step change in scale between laboratory tanks and open sea test sites is too large for many WEC developers, both financially and technically, and an intermediate step as proposed in this project would bridge this current gap.

The HIL testing scheme is considered the state-of-the-art tool to bridge this gap, as it allows creating the relevant environment in which medium to full-scale device subsystems can be extensively tested, demonstrated and validated. Indeed, the HIL technique is used for the development and testing of control strategies for the operation of complex machines and systems, where physical parts of the machine or system are replaced by a simulation. In wave energy applications, the part replaced by a simulation is the global WEC response i.e. the element that converts wave energy into mechanical energy. The mechanical energy is then transferred to other subsystems (e.g. prime mover, PTO) or components (e.g. mechanical interfaces, mooring lines) which is the real hardware under test that closes the simulation loop (see Figure 1, centre). Once a certain subsystem has been tested and validated, its behaviour can be described through numerical models that are fed into the global WEC model with the aim of simulating the device in different operating and non-operating conditions.

Despite this rigorous approach, HIL testing of a sole WEC subsystem (e.g. mechanical structure, PTO, power converter, grid interface, control software, moorings, foundation) allows us to identify and characterize its key aspects as an isolated system. When several components are then assembled together in a device context, inter-dependencies between subsystems can be introduced, leading the entire WEC to have a different behaviour with respect to the simulation and, in the worst case, to unexpected failures. Inter-dependencies can only be captured in a numerical model if accurate representations of all the subsystems are accounted for.

The Dual HIL testing scheme combines two HIL equipped rigs that see two different WEC subsystems simultaneously under test (see Figure 1, right). This novel setup allows to test at the subsystems' levels while addressing their influence at a global WEC level through the numerical model, introducing a fidelity previously unseen in wave energy research. Prime mover, PTO and moorings are the components usually under stress: the key load paths transferred from the wave to the drivetrain and finally to the mooring/ballast/fixed structure can be studied. This novel setup allows to identify and significantly reduce the probability of possible mechanical and electrical failures resulting from components interaction.

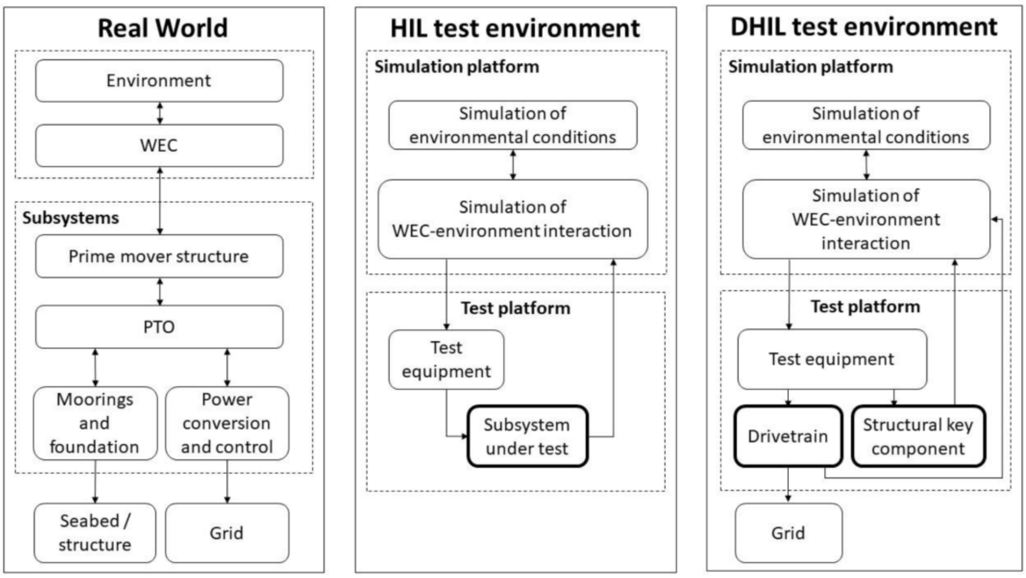

Figure 1 Schematic diagram of real world (left), HIL (centre) and Dual HIL (right) concepts and testing schemes.

Furthermore, the test results allow the development of more accurate WEC numerical models, by informing key modules to describe subsystems settings and inter-dependencies in detail, which are not possible to be quantified in small scale tests. The inclusion of the main subsystems' characteristics in the numerical model is beneficial for the identification of key aspects such as efficiency, reliability, survivability, environmental and techno-economic and can inform the WEC design process in future development steps.

The rigs are a test platform for WEC developers, to minimize the subsystems development risks and costs and to facilitate design convergence of WECs technologies. The HIL rigs and the Dual HIL testing platform are applicable to most WEC types, where subsystems such as drivetrain (linear or rotary), structure (mechanical interfaces in particular), mooring lines, power cables and seals are typically present in the various designs.

2.3 Key objectives and project structure

The project accomplished its main objectives. In particular:

1. Design, fabrication and commissioning of two novel test rigs: one for the complete drivetrain testing and one for structural component testing.
2. Design and realization of a Dual HIL testing platform, to simultaneously test two WEC subsystems.
3. Definition of a complete and thorough test approach related to the identified WEC subsystems, novel methodologies and clear quantitative, test-derived metrics, focusing on performance, reliability and survivability of WECs.
4. Demonstration of the two HIL test rigs, Dual HIL testing platform, novel testing methodology and metrics suitability through a test campaign involving subsystems of different device types.

The technical part of the project was implemented following a work package (WP) structure[1], namely WPs 2 through to 7 – see Figure 2. A brief description of each WP follows:

WP2 – Test rigs parameters and mechanical specifications. The definition of the test rig parameters and mechanical specifications is intrinsically linked with a detailed understanding of the loading environment that a WEC will be subject to during its lifetime. In addition, multiple load sources affect a WEC across a wide range of design situations (e.g. power production, parked, faults in normal operating conditions, etc.), and thus a coupled model that simultaneously accounts for all relevant load sources is key when designing both the WEC and its key-subsystems. Led by Y4C, WP2 achieved the following objectives: a) Definition of a WEC database to characterise the parameters of different WEC types and modes of operation; b) Selection of WEC target deployment sites and relevant environmental conditions, to characterize the range of environmental conditions WECs can be exposed to; c) Creation of WEC numerical models for the selected WECs to simulate various WEC design situations; d) Definition of the mechanical specifications for the test rigs needed to satisfy the combination of WEC types, target deployment sites and design situations considered.

WP3 – Grid integration and Electrical compliance. Power generated by a WEC device and delivered to the electric grid must fulfil quality requirements specified by a grid owner and collected in grid codes, which often differ for each country. It is essential that the parameters of the designed test rigs allow to represent the various conditions required by the country-specific grid codes. Led by SER, WP3 achieved the following objectives: a) Definition of a specification for electrical components of the two test rigs, based on mechanical specifications defined in WP2, relevant grid codes and trends in the grid connection requirements in relevant countries, and available budget; b) Design of an electrical energy storage unit for integration with the drivetrain test rig (selection of storage technology and sizing); c)Development of simulation models for the electrical interface between the PTO output and electric grid for selected WEC types; and d) Integration of the PTO-grid

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[1] https://www.impact-h2020.eu/work-packages/

interface model with numerical models from WP2, thus creating a complete (and generic) wave-to-grid simulation tool to be used for the drivetrain rig HIL and Dual HIL tests.

WP4 – Techno-Economic and Environmental impact evaluation. WP4 was dedicated to the definition of the techno-economic and environmental constraints driving wave energy devices design and testing. The WECs, subsystems and target sites identified in WP2 drove the identification of critical aspects at device and array levels. Led by UCC and in accordance with WP4 objectives, it was studied how each identified subsystem will impact the economics, life cycle and environmental compatibility of the different WEC types.

WP5 – New testing methodologies and metrics. The demonstration of survivability and reliability are at the core of WEC design and the success of a future wave energy industry. This work package aimed to identify new testing methodologies and metrics that support the development of WECs through new rigorous testing approaches, aiming at ensuring the survival of a WEC over the full range of design load cases (DLCs), and to demonstrate its reliability for the duration of its design life. A critical aim of this work package was to accelerate technology development and provide test-based inputs to key design drivers, leading to shorter development pathway to the market. Led by SOCEAN, the following objectives were achieved: a) Harmonisation of the rigs specifications with different testing approaches; b) Definition of a framework / methodology for the accelerated testing WEC design situations to demonstrate the survivability and reliability of a WEC; and c) Definition of metrics to demonstrate the survivability and reliability of a WEC and its key subsystems.

WP6 – Dual HIL testing platform development. WP6 aimed at commissioning the Dual HIL testing platform based on the mechanical, electrical, techno-economic and environmental specifications defined relatively in WP2, WP3, and WP4. Led by VGA, the following objectives were achieved: a) Design, manufacturing, fabrication and commissioning of the drivetrain test rig and of the structural components test rig; b) Integration of the two test rigs to develop the Dual HIL testing platform.

WP7 – Integration of novel test rigs and methodologies. This work package had the overall objective of exploiting the novel test rigs and methodologies according to TAB and wave energy sector needs with the participation of different WEC technologies. Led by Y4C, the following objectives were achieved: a) Identification of critical load pathways to be tested by the Dual HIL test rig; b) Selection of candidate WEC devices and subsystems to be tested using the IMPACT test rigs; c) Definition of a testing campaign to demonstrate the Dual HIL functionalities, followed by a test campaign to measure the performance and survivability of key WEC subsystems, and accelerated tests to demonstrate their reliability.

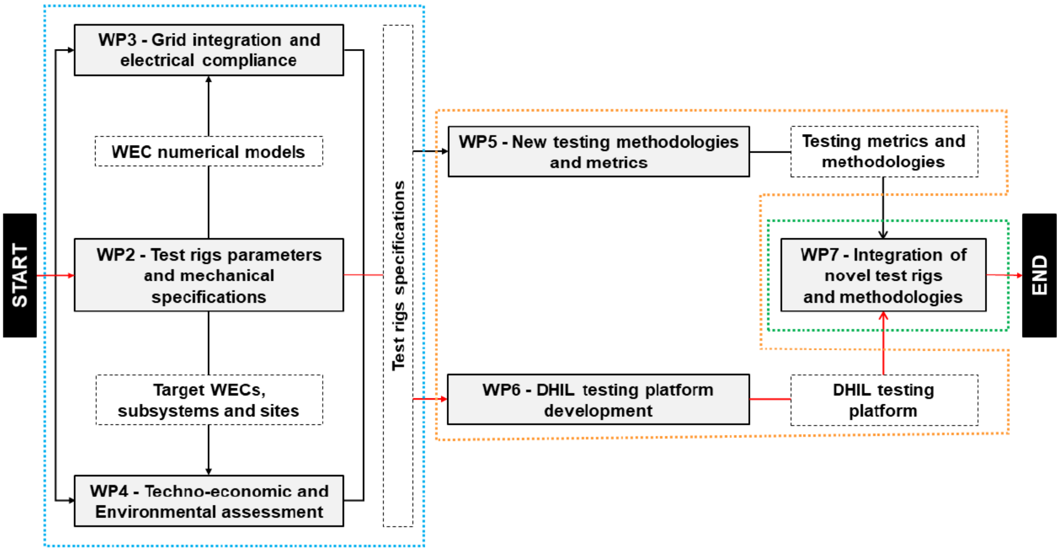

Figure 2 IMPACT's technical work packages and their interaction.

2.4 Project partners

The project was coordinated by VGA s.r.l. with the consortium constituted by a total of 5 partners with different expertise and roles: see Table 1.

Table 1 Partners and related role description.

Partner	Role in IMPACT
VGA	VGA[2] is an Italian original equipment manufacturer. In addition to coordinating the project, VGA was in charge of the drivetrain and structural components HIL test rigs design, manufacturing and commissioning. VGA also commissioned the Dual HIL testing platform and operated the rigs during the project experimental demonstration campaign.
YAVIN FOUR CONSULTANTS Offshore renewable energy experts	Yavin Four Consultants[3] (Y4C) is a Portuguese independent engineering consultancy, solely dedicated to offshore renewable energy (wave, tidal, and wind energy). Y4C performed an estimation of the loading environment that the subsystems are subject to, across relevant DLCs for combinations of target installation sites and WEC types. It also harmonized rigs specifications and managed the final testing phase.
SINTEF	SINTEF Energy Research[4] (SER) is a Norwegian applied research institute dedicated to creating innovative energy solutions. SER analysed grid codes, implemented the PTO-grid model and defined the rigs electrical specifications. Also, they collaborated at the rigs electrical and software design and provided support on the final test phase. SER was also responsible for the communication, dissemination and data management.
UCC University College Cork, Ireland Coláiste na hOllscoile Corcaigh MaREI Energy · Climate · Marine	University College Cork - MaREI[5] evaluated the technical challenges characterizing the WECs and their subsystems. Techno-economic and environmental effect aspects were studied to define the most critical aspects to be addressed by the test rigs and which could influence relevant specifications.
SINTEF	SINTEF Ocean[6] (SOCEAN) is a research institute based in Norway conducting research and innovation related to ocean space for national and international industries. SOCEAN overviewed the choice of WEC database and reference parameters and of the novel testing methodologies. SOCEAN defined novel metrics and checked the overall testing phase execution, from the engagement with WEC developers to the results analysis and final reporting.

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[2] https://www.vgasrl.com/
[3] https://www.yavinfourconsultants.com/
[4] https://www.sintef.no/en/sintef-energy/
[5] https://www.marei.ie/
[6] https://www.sintef.no/en/ocean/

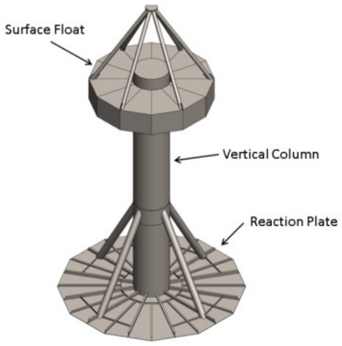
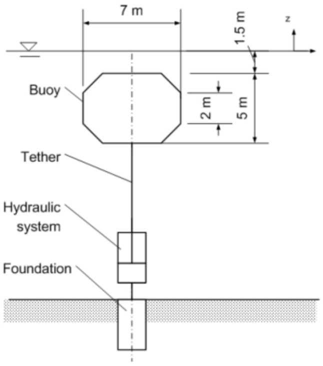
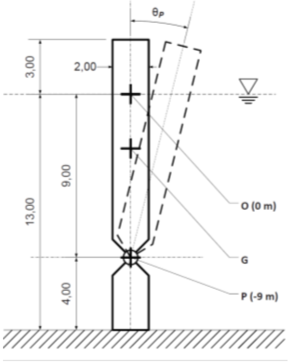
3 Test rigs specifications

The definition of the test rig parameters and mechanical specifications is intrinsically linked with a detailed understanding of the loading environment that a WEC will be subject to during its lifetime. In the initial phase of the IMPACT project, four research areas - mechanical/structural, electrical, techno-economic and environmental – were addressed in parallel to inform the baseline test rigs' developments. These research areas were studied across three different work packages and described in the following sections: 3.1, focusing on mechanical/structural aspects (WP2); 3.2, targeting electrical requirements (WP3); 3.3, covering techno-economic and covering 3.4 environmental aspects (WP4) of relevance to the test rigs' specifications. Finally, section 3.5 focuses on the requirements of an IoT framework embedding digital twin models of both rigs.

3.1 Mechanical and structural requirements.

A WEC model database was conceptualised to characterise the parameters of different WEC types representing a broad range of requirements for different WEC technologies. To obtain specific information for varying WEC types, publicly available information for WEC devices was reviewed and three different WEC models – see Table 2 – were selected to populate the IMPACT WEC database. A numerical model of each WEC type was developed to simulate various WEC design situations. The models were then used to simulate three priority design situations: power generation, power generation under occurrence of a fault and parked / survival state.

Table 2 Baseline WEC models selected for the IMPACT WEC database.

WEC Type	**Point Absorber (PA)**	**Submerged Pressure Differential (SPD) device**	**Oscillating Wave Surge Converter (OWSC)**
Similar to:	OPT PowerBuoy®	CETO 3	Oyster 2
			
Description	Two-body heaving WEC	Single-body WEC	Oscillating flap
Location	Surface	Submerged	Seabed mounted & surface piercing
Reference	Self-referenced	Bottom-referenced	Bottom-referenced
Source of information	Reference Model Project – RM3[7]	NumWEC Project [19]	NumWEC Project [19]

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[7] https://energy.sandia.gov/programs/renewable-energy/water-power/projects/reference-model-project-rmp/

The outcomes of the simulations, namely time-series of displacements, velocities and forces of the WEC and its key sub-systems, were post-processed to derive representative metrics related to performance, reliability and survivability of the devices, and critically reviewed to inform the IMPACT rig(s) testing requirements.

In order to define the test rig parameters and mechanical specifications, the loading environment that a WEC will be subject to during its design life needed to be characterised. Having reviewed a range of WEC types and created a WEC database, the typical environmental conditions a WEC may be exposed to, namely the wave climate, with a focus on European waters were assessed. Other environmental conditions that may affect WEC reliability (e.g. biofouling, corrosion) were also considered.

A shortlist of potential deployment sites, and the associated wave conditions characterised for both normal and extreme sea state scenarios (Figure 3), was defined following a set of three sequential criteria (or filters) – Table 3.

Table 3 Site shortlisting criteria: Filters 1 to 3 are applied sequentially.

Filter 1	**Filter 2**	**Filter 3**
Conditions that result in: • Moderate power sites (i.e. Class 2 or Class 3 wave resource site class) • Maximize WEC performance: ○ Optimised for a relatively high proportion of sea states ○ Limited effect of power capping on the MAEP estimates ○ Moderate to high relative capture width	Conditions that result in: • Higher power sites (i.e. upper end of Class 2 or Class 3 wave resource site class) • Moderate WEC performance: Less stringent filtering criteria for optimised sea states and power capping ratio	Conditions that result in: • Higher power sites (i.e. Class 3 wave resource site class) • Highest MAEP estimates

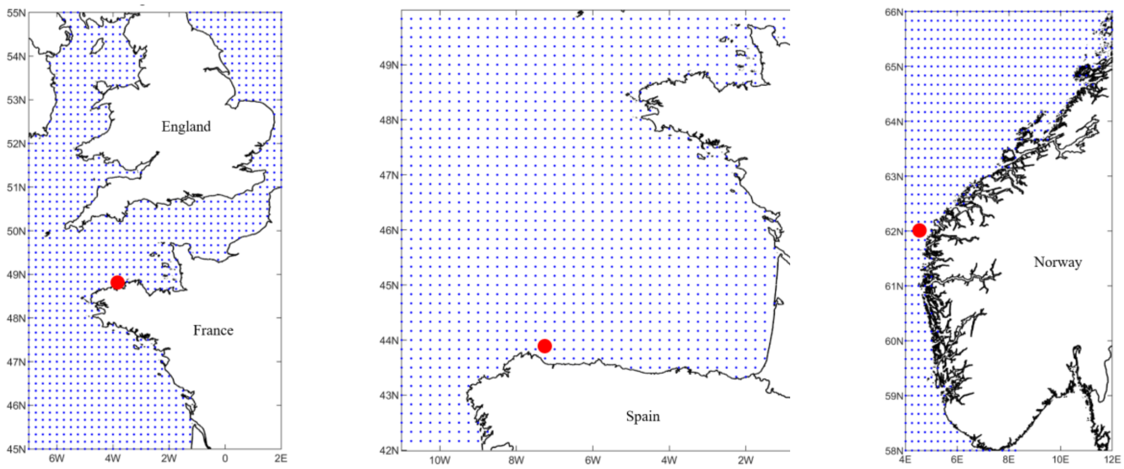

Figure 3 Site characterisation: the three deployment sites in IMPACT.

With the specific goal of conceptualising a load envelope for designing the IMPACT rigs, three DLCs were prioritised in line with the aforementioned three priority design situations: DLC 1.1 (*Power Production*), DLC 2.1 (*Power Production Plus Fault*) and DLC 6.1 (*Parked / Survival*). These DLCs were selected with the aim of exploring the widest load range associated to 'performance', 'reliability' and 'survivability' key evaluation areas applicable to the shortlisted WECs and deployment sites, while maintaining the computational effort at an affordable level. The three DLCs were simulated via the WEC-Sim models to provide output time-series of displacements, velocities and forces for critical subsystems of the WECs, including the PTO and, where applicable, the mooring system.

The resulting time-series were post-processed to extrapolate selected key metrics to further inform the design of the IMPACT rigs. The metrics were based on several parameters including PTO power, force and speed, and mooring force at the fairlead. The results showed that the load envelope associated to a given device can vary significantly when different DLCs are evaluated. Static and dynamic (including fatigue) load estimates may be relevant for multiple WEC design challenges, under e.g. operational, fault and / or parked states. This result highlights the importance of a design brief at an early stage of a WEC's design process, to ensure that all foreseeable working conditions are considered from inception.

With the aim of identifying key environmental parameters that could be relevant for accelerated testing / reliability assessment of WEC components, an extensive review of relevant standards / guidance reports was carried out. Among other parameters, marine growth and corrosion were selected for consideration within IMPACT – also noting that these are targeted by past and ongoing R&D projects such as Waveboost[8], Oceanic[9], SEASNAKE[10] and VALID[11].

Concerning reliability issues, marine growth may be regarded as a medium-level risk failure mechanism, potentially increasing the rate of wear and fatigue loading on e.g. mooring lines. About its effect on the performance of WECs, it was concluded that only a few studies have been published focusing on this issue, and that these are typically based on both physical and numerical modelling for evaluating specific phenomena related to mass increase, changes in drag coefficients, variations in fatigue life and power absorption. In specific cases, the overall system mass was found to increase between 2% to 10% in a 10-year timeframe.

Focusing on accelerated testing for reliability assessment, corrosion accelerated tests were deemed as particularly interesting to study fatigue-corrosion dependencies on failures and corresponding extrapolation of reliability test-based metrics. On the other hand, the review highlighted that determining the fatigue S-N curve in similar environmental conditions might be very challenging, because the corrosion-fatigue crack growth could be faster by a factor of up to six in typical wave frequencies than at higher frequencies [6]. Appropriate modifications of physical and/or electrochemical properties involved in the redox reactions would accelerate the corrosion process. Several corrosion-fatigue acceleration methods were identified, e.g. salt spray, applied potential, increased temperature levels and oxygen contents [7].

3.2 Electrical requirements

The drivetrain test rig was built for the purpose of dry testing the overall drivetrain of a WEC, from the input mechanical power to the point of common coupling with the grid. Part of the testing regime is related to electrical aspects where the interaction with an electrical grid plays a relevant role. Ideally, the test rig should allow to reproduce the various electrical conditions required by the country-specific grid codes in various operational modes (e.g., normal operating conditions, start-up, and extreme load conditions) also including grid disturbances.

Grid codes are a set of requirements for connecting all types of power generating plants to the electric grid. These criteria ensure the safe and reliable operation of the grid. Despite efforts to harmonise these, there are still considerable differences between countries and regions. Therefore, information from relevant grid codes

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[8] https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/ocean/waveboost

[9] http://oceanic-project.eu/biofouling-database/

[10] https://oceanenergy-sweden.se/seasnake/

[11] https://www.validhtp.eu/

that is pertinent to the test approach was collected to support the test rig sizing for performing grid compliancy tests.

Afterwards, a complete wave-to-wire model, capable of representing the system behaviour from the incident waves to the grid connection of wave energy converters, was developed in MATLAB/Simulink. This model included the hydrodynamics of oscillating bodies, PTO models with and without hydraulic system, electromechanical components for the energy conversion and a configurable electrical grid model; their archetypical structure is shown in Figure 4. The electrical model is referred as PTO-grid interface model and is integrated within the WEC-Sim tool, which solves the equation of motion of the body including the PTO systems. The wave-to-wire model was tested in a set of relevant conditions to validate its operation and verify its main features. More details of the model and simulation results can be found in a conference paper [8].

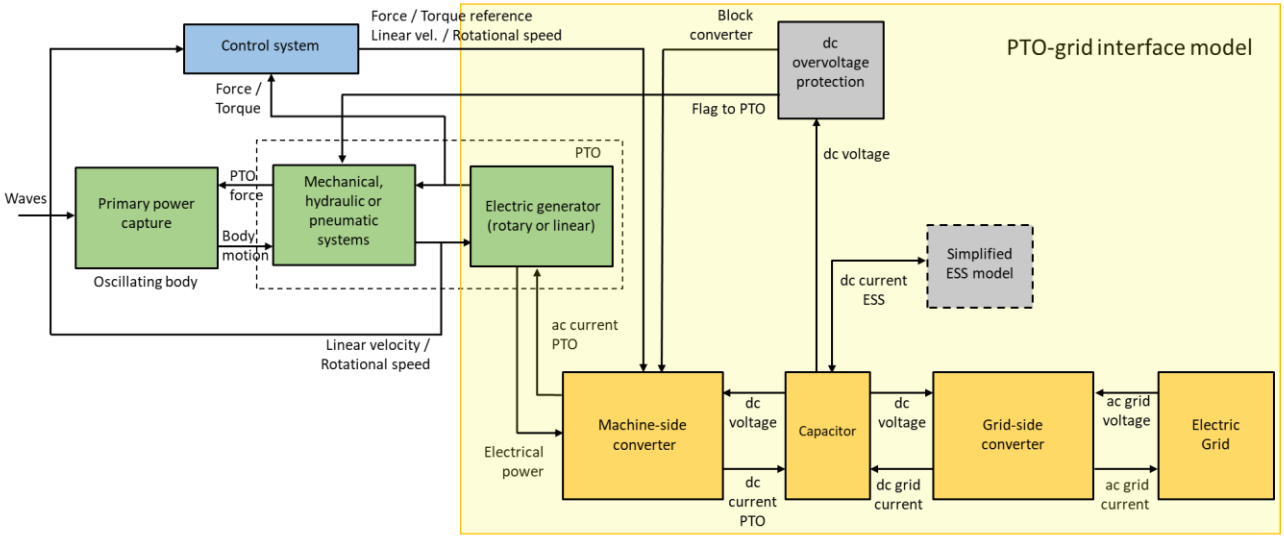

Figure 4 Overview of a wave-to-wire model for oscillating bodies including grid interface and electrical grid model. The main components of the PTO-grid interface model are highlighted [8].

The drivetrain test rig simulates the wave energy converter's prime mover, exerting a load on the power take-off. In addition, grid code compliance also requires grid emulation. Then, the test rig's architecture and candidates for grid emulator converters were addressed by assessing a few options and the existing setup at VGA facilities. When the rig's power exceeds the local grid capacity, an energy storage system is needed. The integration of an energy storage system (ESS) was thoroughly evaluated and a methodology for specification and sizing of ESSs for test rigs was developed. A manuscript presenting the methodology and main results are currently under review in a scientific journal. Finally, the electrical specifications included a review of market products, with examples and recommendations. Such recommendations emphasized balancing performance, application, and the cost for grid emulation options to ensure optimal functionality and budget efficiency.

3.3 FMECA and Techno-economic analysis

A Failure Mode, Effects and Criticality Analysis (FMECA) and a techno-economic study were conducted for each of the WEC archetypes presented in Table 2. An overall description of the FMECA approach is illustrated in Figure 5.

The FMECA used the Offshore and onshore REliability DAta (OREDA) database and other literature sources to produce data related to the failure rates of the most common component failure modes and failure mechanism in generic WEC subsystems. It evaluated metrics for the most frequently failing parts, and the most common failure modes and failure mechanisms for 34 components and 180 parts. The qualitative risk indicators and quantitative criticality numbers produced in the FMECA provided a better understanding of the potentially critical parts, failure modes and failure mechanisms at the component level, which can support the design work of a WEC during later project stages.

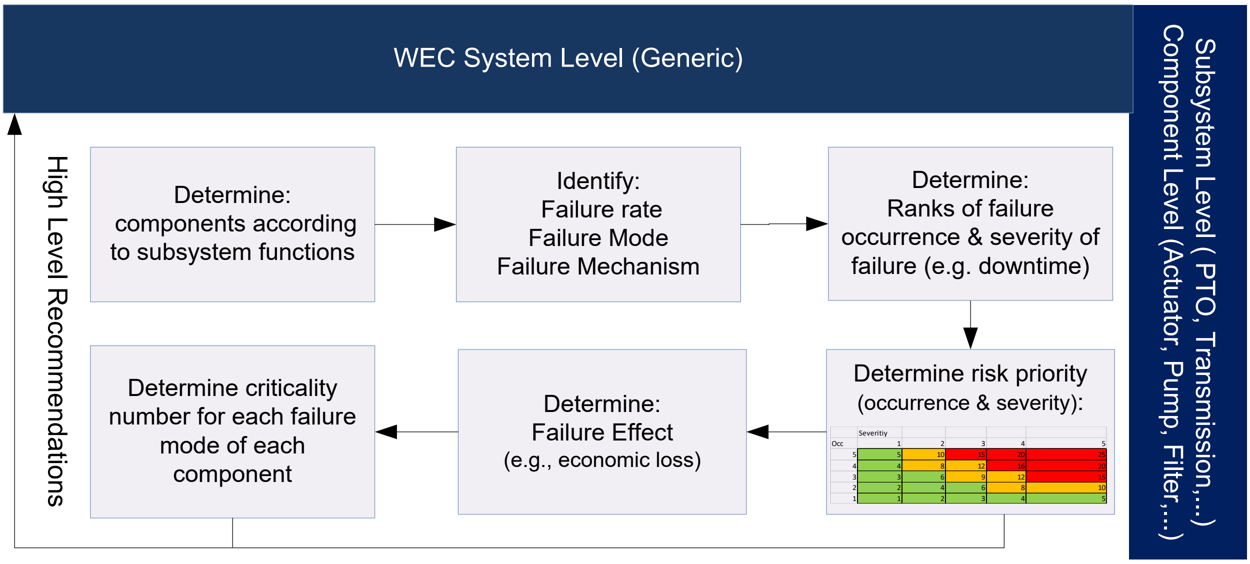

Figure 5 An overall description of the FMECA.

In the techno-economic analysis, several scenarios were created. A comprehensive Operation and Maintenance (O&M) tool was developed and used to analyse the failure distribution at component level and to calculate statistics of the downtime, down-energy and energy production (see Figure 6) for a base project with varying number of WECs at the three deployment locations. Redundancy scenarios were created for PTO components with a high failure rate, but relatively low mass and cost. Several sensitivity analyses to failure rates and electricity sale rates were conducted. Some of the metrics analysed by this study were: the numbers of failures and their distributions, the electricity delivered to the grid, the Operating Expenditure (OPEX), the Capital Expenditure (CAPEX), and the Levelized Cost of Energy (LCOE).

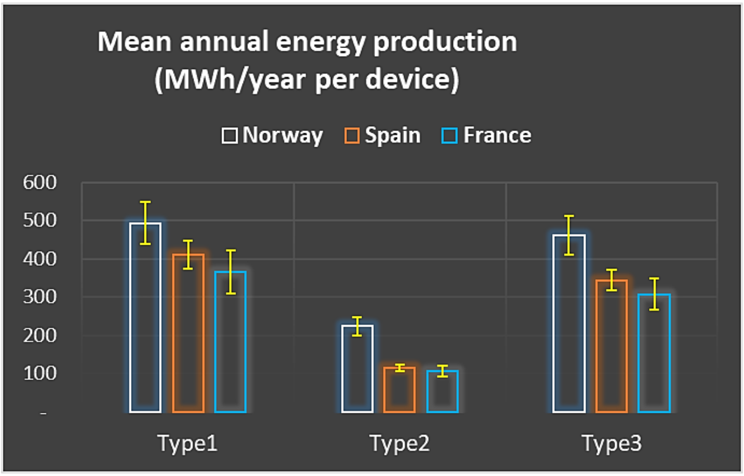

Figure 6 Expected energy production of the three WEC types in three regions.

Findings indicated which components are more critical than others and to what extent. For example, it was seen that the motor, filter, frequency converter, valve, pressure sensor and hydraulic ram fail at high rates and as such are critical components. Moreover, the OPEX is strongly related to the decreased energy production during downtime periods due to fails and the associated waiting periods for weather windows, which varies with the deployment location.

Three main findings stood out from the techno-economic assessment, with possible implications on further development of the studied WECs:

1. Minimum redundancy measures on relatively cheap components, for example valves, filters and pressure sensors, may significantly increase the overall system performance: for a CAPEX increase of less than 0.4%, there is (on average) a decrease of 20% of the number of failures and an increase in energy production of 0.4% to 1%. This suggests that such components might not require high-priority R&D for wave energy applications, as implementing redundancy for these may be easily affordable within project budgets.
2. Repairing the prime mover may have a significant negative impact on the overall project efficiency, due to the high cost: reducing the failure rate of prime movers should be a priority.
3. There is a wide uncertainty regarding the output metrics (e.g. delivered energy, O&M costs) associated with the operation of the WECs.

The data and results of the techno-economic analysis carried out supported the assessment of the reliability and techno-economic performance of the WECs and subsystems were considered in the IMPACT project. Specifically, they identified the components/ subsystems which have the largest influence on WEC failure as potential candidates for further testing to reduce their respective failure rates.

3.4 Environmental impact related specifications

A detailed review was carried out concerning environmental aspects resorting to three different sources: scientific literature, project reports from Marine Renewable Energy (MRE) deployment sites (so-called ‘grey literature’) and information from Environmental Impact Assessments (EIA). The objective was to outline the most studied environmental impacts (see Figure 7) and focus on identifying known impacts of WECs and those relevant to the IMPACT project.

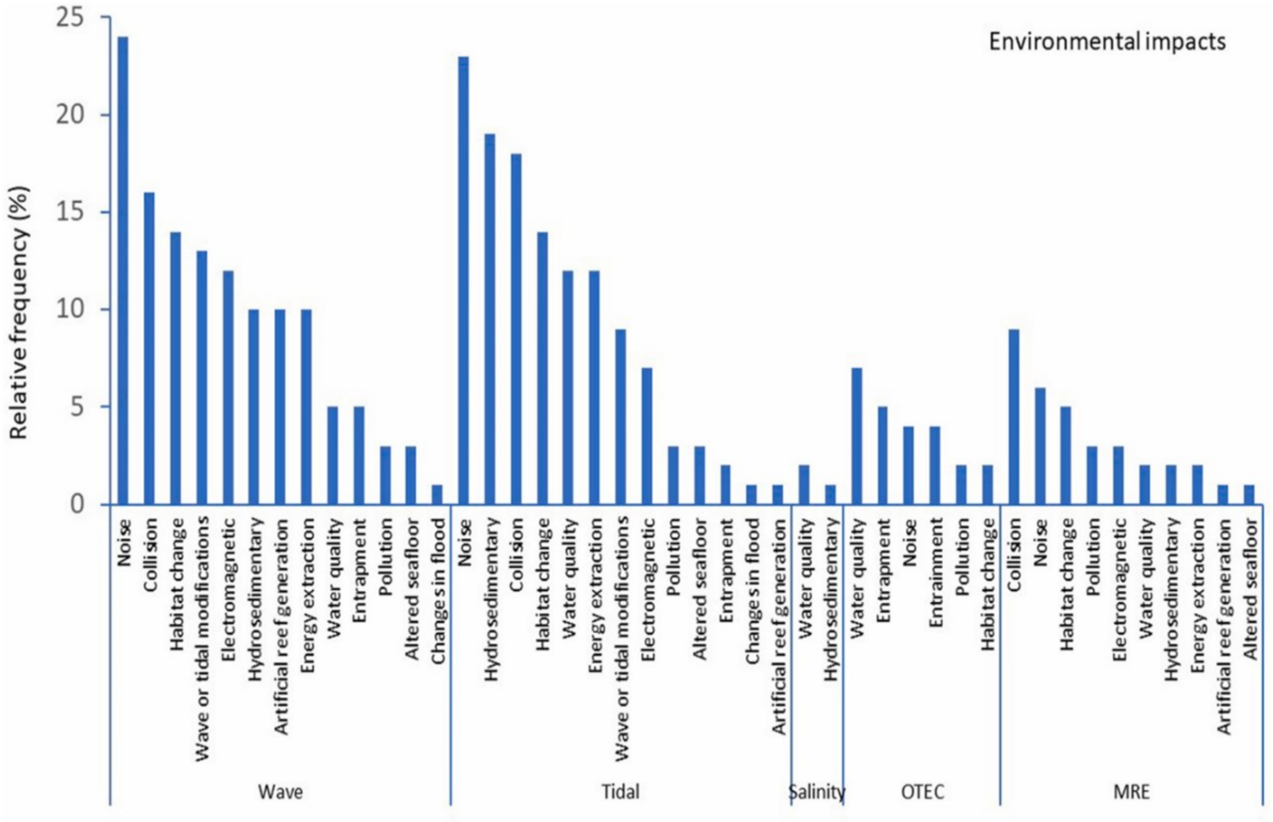

Figure 7 A summary of data from 190 studies. It proves that wave and tidal devices show a similar pattern in terms of the impacts of interest, with noise being the dominant impact [9].

Areas in which there is insufficient evidence or high uncertainty were highlighted and suggestions were made as to how information gaps may be filled. Existing legal frameworks and industry best practices that are relevant to the environmental impacts of MRE were also outlined and the analysis of broader marine law and policy was included to ensure that the environmental implications of decisions are taken into account at the earliest possible stage during the development process.

The conclusion of this effort was that information available at present in what relates to Environmental Impact is not adequate to provide detailed guidance for the testing phase of WEC development. Nevertheless, while environmental considerations are not typically considered at the early stages of development of MRE devices, there are legal, policy, and ethical frameworks, as to why devices should be designed to have a minimum environmental impact. Furthermore, understanding of the potential impacts as early as possible could help to streamline in-situ testing and deployment stages.

3.5 Digital twin and IoT network requirements

One of the objectives of IMPACT was to develop and implement Digital Twin (DT) models of both rigs supported by Structural Health Monitoring (SHM) and Condition Monitoring (CM). This task targeted the development of a generic, public domain, hybrid IoT framework embedding both EDGE (local computer) and CLOUD (server) processing, together with visualization of physical and virtual test data. In terms of model validation, a set of metrics for evaluating the differences between results from physical tests and digital twin simulations were also proposed (see Table 4).

The DT was integrated in an IoT framework providing additional information tests and simulations of the WEC subsystems and components that can be shared with all stakeholders (laboratories, quality assurance engineers, customers, etc.) with no access to traditional test software. The framework was also used for monitoring key test measurements, including the integration of DT models augmented with a Finite Element model of the test rig for strain/stress-based fatigue analysis.

Table 4 Digital Twin validation metrics.

Metric	Requirement	Comment
Simulation speed	Real time co-simulation based on Functional Mock-up Unit or Reduced Order Model	Real time co-simulation is not strictly required but an enabler for state of art digital twin monitoring.
Simulation robustness	Sample frequency from physical test applied without convergence problems	Robust solver performance is important to keep the physical and digital twin model in sync.
Mass stiffness and damping properties	Deviations should be < 5% for dominant modes	Must be tuned against physical tests with accelerometers.
Dynamic forces accuracy	Deviations should be < 20%	Primary variable sensitive to model mass, damping and stiffness distribution.
Displacements, velocities and accelerations	Deviations should be < 10%	Primary variables less sensitive to model detailing.
Stresses and strains	Deviations should be < 10%	These are inputs to fatigue analysis very sensitive to model detailing and predicted loads. This metrics is a trade of between simulation speed and accuracy.
Power prediction	Deviations should be < 20%	Sensitive to predicted forces and speeds.

4 Testing methodologies and metrics

From the requirements and preliminary specifications defined in Section 3, a revision was carried out and a final specification listing was produced concerning the drivetrain and the structural components rigs.

Specifically, a matching exercise between the input requirements (‘demand’) and the initial rigs capacity (‘supply’) was conducted. To mitigate any identified mismatch between the ‘demand’ and ‘supply’, a range of mitigation strategies was presented: these included scaling, advanced sub-system modelling, and advanced control techniques. The overall test rigs specifications were eventually derived, including details on the rigs’ architecture and specific features such as the capability to submerge specimens in synthetic sea water.

4.1 Novel testing methodologies

Once the requirements had been reassessed and the specifications revised, testing methodologies were defined for use in the IMPACT rigs. The activity culminated in the conceptualisation of a novel testing framework relating to key evaluation areas in WEC design: Performance, Reliability and Survivability.

4.1.1 Testing approaches within wave energy technologies development

The development of a novel technology typically requires a mix of design, simulation, prototyping and testing activities at a range of scales and in different environments. To measure the maturity of a technology during the development process and to allow a consistent comparison between different types of technologies, the development pathway may be framed into a series of stages , described in Table 5.

The use of TRLs has been widely adopted in the wave energy sector to compare e.g. the maturity of the different technologies under development. In a recent guidance document for wave technology issued by the International Energy Agency (IEA) [10], a staged approach for the technology development of ocean energy was proposed. Furthermore, Technology Performance Levels (TPLs) have also been introduced to quantify and classify the techno-economic performance of WECs, in conjunction with TRLs / stages.

Table 5 Readiness, development, and performance levels.

Technology Readiness Level (TRL)	Stages - IEA	Technology Performance Level (TPL)
1. Basic principles observed	0. Concept creation	Majority (TPL 1), some (TPL2), or a minority (TPL3), of key performance characteristics & cost drivers do not satisfy and present a barrier to potential economic viability. To achieve economic viability under distinctive and favourable market and operational conditions some improvements are required concerning some: - TPL4: key technology implementation and fundamental concepts. - TPL5: some key technology implementation. TPL6: Majority of key performance characteristics & cost drivers satisfy potential economic viability under distinctive and favourable market and operational conditions. Competitive with other renewable energy sources given favourable support (TPL7), sustainable support (TPL8), or without special support (TPL9) mechanism.
2. Technology concept formulated 3. Experimental proof of concept	1. Concept development	
4. Technology validated in lab	2. Design optimisation	
5. Technology validated in relevant environment 6. Technology demonstrated in relevant environment	3. Scaled demonstration	
7. System prototype demonstration in operational environment 8. System complete and qualified	4. Commercial-scale single device demonstration	
9. Actual system proven in operational environment	5. Commercial-scale array demonstration	

From a testing perspective, progressing to the highest TRL requires the validation and demonstration of the technology, firstly in a laboratory, and subsequently in both relevant and operational environments. In the IEA framework, the testing activities corresponding to Stages 1 and 2 (i.e. TRL 2 to 4) are to be performed only in a controlled environment (laboratory). Subsequently, it is suggested that Stages 3 and 4 (TRL 5 to 8) include both laboratory (especially for sub-systems) and open ocean testing (for representatively scaled and / or full-scale devices). Finally, Stage 5 (i.e. TRL 9) encompasses system testing in an uncontrolled environment (open ocean) except for reliability aspects, which requires rig testing still at commercial-scale array demonstration.

Regardless of the stage-based approach considered, testing is crucial in developing WEC technologies, especially when using a low-risk, low-cost approach that prioritizes performance over maturity at a low TRL. This method optimizes techno-economic potential with less capital [11]. However, uncertainties in predicting mature system characteristics and limitations in simulation and modelling can hinder this approach.

The IMPACT project aimed at increasing the reliability of the TPL assessment, through empirical evidence and experience from focused sub-system early testing, targeting key evaluation areas of a WEC such as Performance, Reliability and Survivability.

It is also worth noticing that testing plays a crucial role in the Technology Qualification (TQ) process, especially for technologies without predefined standards. For example, DNV outlines this process in three steps [12][13]: "Technology Assessment," "Qualification Plan Definition," and "Technology Qualification." Each step's completion results in a "Statement of Feasibility," "Endorsement of Qualification Plan," and "Technology Certificate." The IMPACT test rigs and methodologies were specifically designed to support early testing of critical sub-systems and components, aligning well with the TQ process.

4.1.2 A novel testing framework

A methodology for testing such critical subsystems and components was conceptualised and detailed. At a high-level, the IMPACT methodology framework is essentially composed by three layers of different 'building blocks', as illustrated in Figure 8 and listed as follows:

- *Foundation blocks*, which specify the stage of the testing programme i.e. pre-processing, processing or post-processing.
- *Functional blocks*, which relate to the identification of the main tasks at each testing stage.
- *Input blocks*, where specific inputs to each *Functional* building block are introduced.

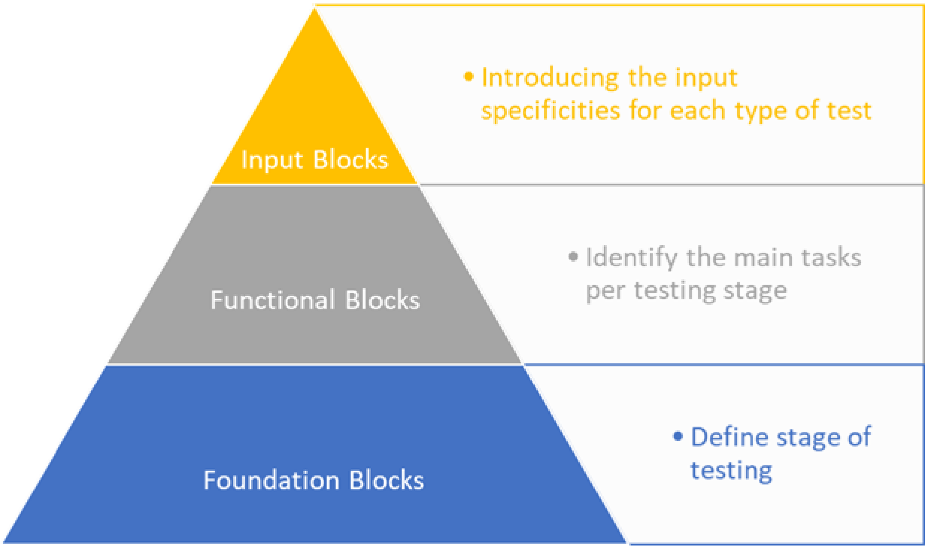

Figure 8 IMPACT testing methodology framework – 'building block' layers.

As one of the first steps within the Foundation blocks, a key task to be conducted at pre-processing stage consists in defining the testing strategy to be adopted. The testing strategies developed within the IMPACT project are primarily based on the adoption of HIL and accelerated testing principles (either in isolation or, potentially, in combination).

In a HIL scheme, a system is typically decomposed into its subsystems and components which may be represented either by virtual or physical equivalents on the test rig. The interaction between virtual and physical representations of the subsystems / components is typically simulated via the use of real-time target machines which control the actuator of the test rig. An analogy between a typical ocean deployment and the principles of HIL testing is illustrated Figure 9. In particular, Figure 9 (left) shows an example of the interactions between the subsystems of a WEC, the environment, the seabed and / or the electrical grid in an ocean deployment. In Figure 9 (centre), an example of a HIL application is provided: the PTO / control subsystem is a physical model, while the other subsystems are represented by numerical equivalents.

The IMPACT project aimed to extend the potential benefits of a HIL approach to a Dual HIL approach, where more than one subsystem is represented via physical models. Figure 9 (right) shows an example application of a Dual HIL scheme, where the PTO / control and the reaction subsystems are represented by physical models, actuated by two different rigs which are in turn commanded by a single real-time machine. A Dual HIL approach has the potential to capture the inter-dependencies of two subsystems / components via their physical representations, thus potentially increasing the level of fidelity of the overall testing campaign. For example, a Dual HIL testing approach could provide data on if and how the interdependencies between subsystems affect the failure mechanisms and failure modes of the WEC.

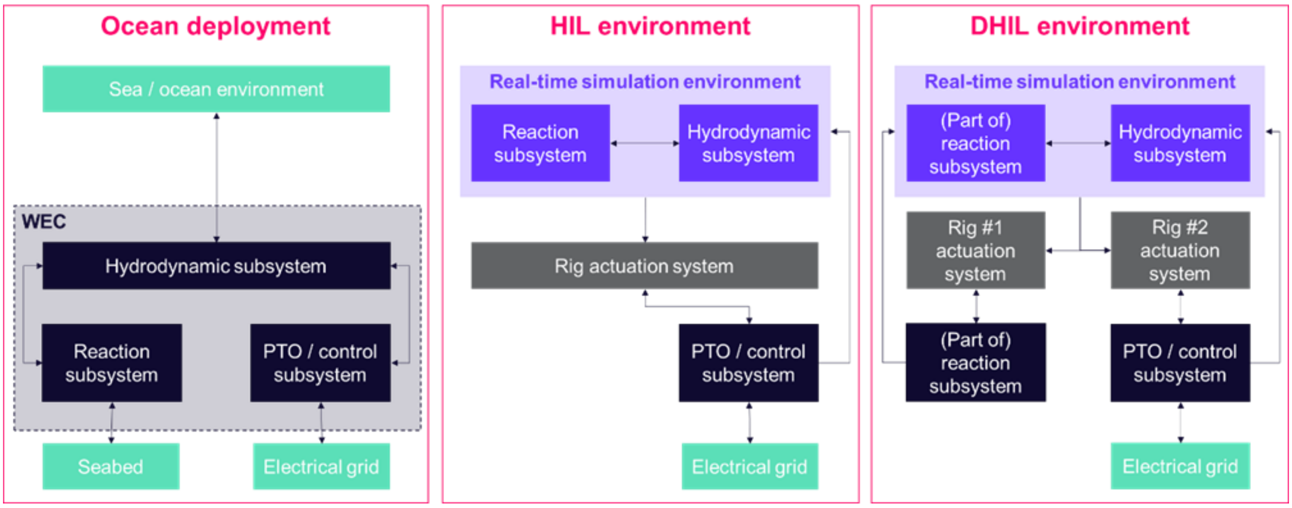

Figure 9 Schematic diagram of an ocean deployment (left), HIL testing environment (centre) and Dual HIL testing environment (right).

At the core of the IMPACT testing framework there is also accelerated testing. At a high-level, accelerated testing is a testing technique which aims to assess key metrics related to different evaluation areas (e.g. Reliability, Survivability) in a reduced amount of time. Two types of accelerated testing may essentially be considered:

- Qualitative Accelerated Testing (QualAT).
- Quantitative Accelerated Testing (QuanAT).

Figure 10 provides an overview of the main steps involved in the definition of both a QualAT and a QuanAT strategy. QualAT typically aims to identify and characterise failure-related criticalities in a subsystem and/or component, following a qualitative approach.

For example, QualAT may support the assessment of the importance of multiple variables towards failure of a subsystem / component and the gathering of data for the conceptualisation of a numerical model. Most often, the loading scenario conceptualised in a QualAT testing is not directly related to the environmental conditions the component will experience at the deployment site, but rather on a wide range and/or large variation in input conditions, aiming to characterise the failure profile of the component.

Complementarily to QualAT, QuanAT is conceptually better suited for the detailed testing of subsystems and/or components, aiming to quantify the failure-time and/or degradation pattern at typical usage levels. QuanAT may allow quantifying the expected damage levels of the subsystem/component faster than real-time, potentially following different approaches e.g. manipulating the input load and/or material resistance or using proxies of the environmental conditions at the deployment site.

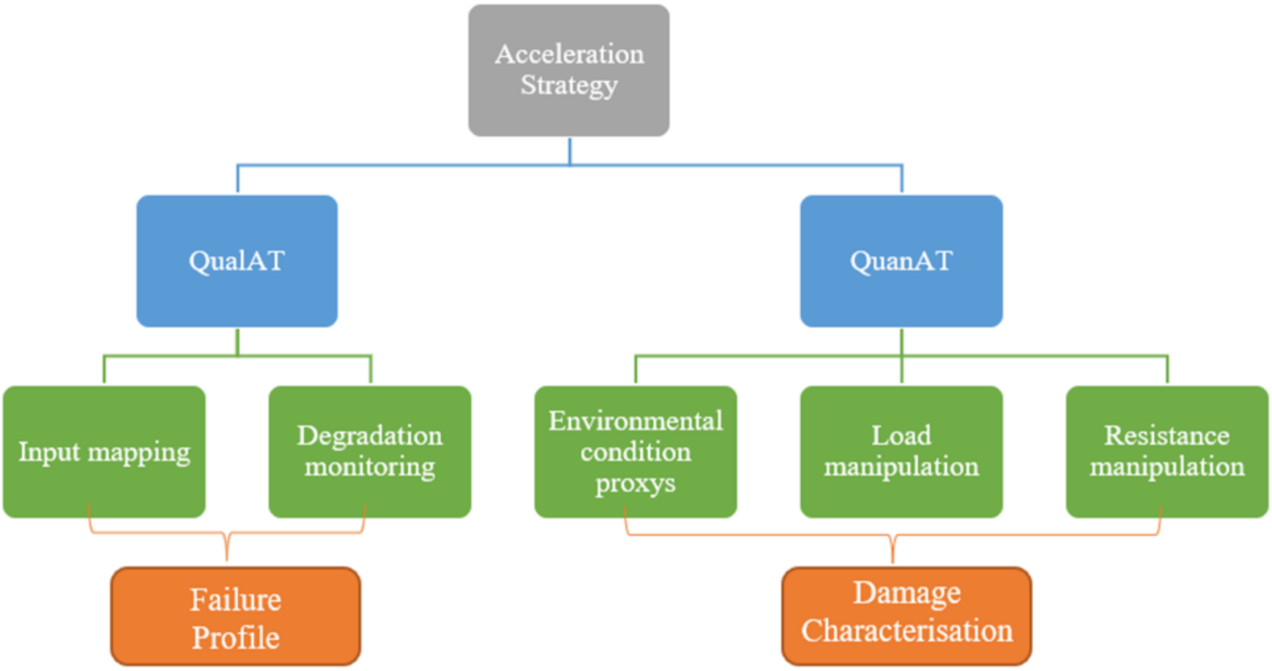

Figure 10 Overview of the main steps involved in the definition of an accelerated testing strategy.

A significant effort across all testing stages is dedicated to monitoring a range of test parameters and converting them into key metrics.

Table 6 outlines the Functional blocks and the Input blocks for each testing stage of the IMPACT methodology framework. For example, after defining the conditions to be replicated during the test, one of the tasks to be conducted at the pre-processing stage is dedicated to identification of the testing strategy to be used (e.g. HIL, dual HIL or accelerated), related setup and specification of actuation systems and the sensors/transducers to be installed on the rig.

At the processing stage, the Functional blocks include installation and calibration tasks (where all instruments are integrated with a Data Acquisition, DAQ, system), basic testing tasks (mainly involving the DUT characterization) and advanced tests (involving the identified testing strategy).

At post-processing stage, after inspecting both rig and DUT to identify eventual damages, the acquired data is firstly checked for assessing the desired quality (in terms of number of tests and signal levels). Afterwards, results are analysed to derive concise yet representative test metrics.

Table 6 IMPACT testing methodology framework with Foundation (blue), Functional (grey) and Input (yellow) building blocks. If adopting a dual HIL approach, two Devices Under Tests are simultaneously tested on the structural components and drivetrain rigs, respectively.

Foundation block	Functional block	Input block	Outline description
Pre-processing	Test conditions	Environmental conditions	Definition of the reference environmental conditions for the WEC including e.g. wave, wind, currents, marine growth, ice, etc.
		WEC status	Definition of the WEC machine status corresponding to the planned test activity e.g. production, parked, grid loss, etc.
	Test set-up	Testing strategy	Definition of the testing strategy to be applied e.g. HIL / Dual HIL, real-time, accelerated, etc.
		Scaling assessment	Identification of scaling needs to match the rig(s) capacity for testing.
		Target machine set-up	Set-up of the real-time target machine (only for HIL / Dual HIL testing).
	Rig set-up	Hardware set-up	Set-up of all rig(s) for testing e.g. actuators, drives, electrical infrastructure, etc.
		Preliminary rig test	Preliminary testing of rig(s) to check e.g. the correct installation and commissioning of hardware, actuator calibration, etc.
Processing	DUT & transducers installation	DUT installation	Installation of the DUT(s) on the rig(s).
		DAQ system set-up	Set-up of transducers and integration with a DAQ system.
	Basic testing	Signal tests	Check that all signals commanded to / acquired from the rig are correct.
		DUT model calibration	Calibration of specific DUT(s) properties, based on the test specificities.
		DUT characterisation	Characterisation of the DUT(s) e.g. PTO efficiency, mooring stiffness, etc.
	Advanced testing	DLC x.x test programme	Implementation of the actual IMPACT testing campaign.
		Signal monitoring (DUT and rig)	Effective monitoring of all signals during testing.
Post-processing	Inspection	DUT status	Inspection of the DUT(s) after testing to check for potential damage / alterations.
		Rig status	Inspection of the DUT(s) after testing to check for potential damage / alterations.
	Data quality	Data quality check	Quality check on acquired data e.g. missing data, outliers, etc.
		Raw data filtering	Filtering of data to remove e.g. noise.
	Data analysis and reporting	Metrics assessment	Assessment of test-specific metrics e.g. Performance, Reliability, Survivability metrics.
		Uncertainty assessment	Assessment of uncertainty in the derived test results and test-specific metrics.
		Reporting	Final reporting activity of the test.

4.2 Metrics

As for any technology, the need to consider, identify and formulate performance requirements and related assessment criteria is an important subject in WEC development. These requirements allow to ultimately characterise each device through techno-economic indicators to compare between technologies and verify the characteristics of the product throughout the development stages. This assessment is ideally carried out through the application of metrics complying with attributes such as: precise, repeatable, specific, measurable, established, globally recognized, etc. [14].

Establishing metrics for the assessment of WECs and its components is fundamentally challenging. In addition to the difficulty of establishing metrics per se, the wave energy sector includes many different designs. Also, there is limited operation/testing of prototypes and an overall lack of knowledge sharing between developers.

4.2.1 Existing metrics

Notwithstanding the above difficulties, a considerable effort has been employed to establish WEC specific performance metrics, notably by the International Electrotechnical Commission (IEC), Ocean Energy Systems (OES) and the European Marine Energy Centre (EMEC), among others, in the form of technical specifications and guidelines, while several publications and research projects have analysed and proposed metrics to be applied. A compilation and review of existing metrics was carried out under IMPACT, targeting selected evaluation criteria [15]:

- Under the *Performance* evaluation area:
    - *Power capture*. The process of converting energy from the natural resource by the interaction with a device, making it available as an input to a PTO sub-system.
    - *Power conversion*. Represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity.
- *Reliability*. The probability that an item can perform a necessary function under given conditions for a given time interval.
- *Survivability*. A measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event has passed.
- *Techno-economics*. Denotes evaluation of indicators which are directly related to costs. Sometimes identified as performance indicators, these include the following evaluation areas: availability, affordability, and maintainability.

The review was carried out resorting to listed metrics in standards, guidelines, and recommendations, specific to wave energy conversion, other published proposed metrics specific to wave energy conversion, and relevant test-derived metrics in other relatable industries or sectors. The objective was to identify relevant metrics and works on the subject to support the definition of novel key metrics under IMPACT, not limited to test driven ones. A list of metrics is given in Appendix A. Further details and discussion can be found in [16].

4.2.2 Novel metrics

It was an objective of IMPACT to define key test-derived metrics to monitor in a context of technology development, model validation and structural health monitoring. In this regard, a set of novel, or at least not extensively used metrics, were proposed which can prospectively benefit from test-derived data obtained using IMPACT drivetrain and structural test rigs. The novel metrics follow the framework in Section 4.1.2, by addressing aspects related to the three main evaluation areas established therein: *Performance*, *Reliability*, and *Survivability*. The novel metrics, their formats, short description, and main remarks are listed in Table 7. At the time of the submission of this report, a research paper is currently being finished to submit for publication exploiting the relevance of each of these.

Table 7 List of novel metrics.

Evaluation area	**Metric**	**Short description**	**Remark**
Performance	Output variability curve (OVC)	Estimation of the variability of the output power of the WEC over a year.	The output variability is defined as: $\mathrm{OV} = \frac{P - Pr}{Pr}$ where P is the average output power and Pr is the rated power of the WEC (both in kW). The average output power can be extracted from the WEC power matrix and the site scatter diagram. Presented as a curve, it represents the percentage of year in the x-axis and the output variability (OV) in the y-axis.
Performance	PTO duty ratio	High-level characterisation of the effort that the PTO has to sustain to generate output electrical power.	Defined as the ratio between the average PTO power (or energy) and the Root-Mean-Square (RMS) PTO load i.e.: $\overline{P_{PTO}}/F_{PTO,RMS}$ (short-term based RMS) or $MAEP/F_{PTO,RMS}$ (occurrence-weighted RMS)
Performance	Frequency based control optimality (CO)	A measure of how the performance of the PTO relates to an optimally controlled PTO.	Defined as the ratio between the mean absorbed power and the mean absorbed power under optimal control conditions, i.e.: $\bar{P}/\bar{P}_{OPT}$ (short-term, sea state oriented) or $MAEP/MAEP_{OPT}$ (long-term, site oriented).
Performance	Control spectral performance (CSP)	A measure of how the performance of the PTO is affected by the irregularity of the waves.	Defined as the ratio between the capture length and the capture length at the peak (or mean) wave period, i.e.: $L/L_{T_e;T_p}$ (short-term, sea state oriented) or $\bar{L}/\bar{L}_{T_e;T_p}$ (long-term, site oriented)
Reliability	Fatigue ratio	Characterises the fatigue effort a subsystem / component e.g. PTO, power cable, mooring element etc. has to sustain for the WEC to generate output electrical power.	Defined as the ratio between the average PTO power (or energy) and the subsystem / component Damage Equivalent Load (DEL) i.e.: $\overline{P_{PTO}}/F_{DEL}$ (short-term DEL) or $MAEP/F_{DEL}$ (long-term DEL)
Survivability	Ultimate load ratio	Characterises the extreme mechanical effort a subsystem / component has to sustain for the WEC to generate output electrical power.	Defined as the ratio between the average PTO power (or energy) and the subsystem / component Ultimate Limit State (ULS) load i.e.: $\overline{P_{PTO}}/F_{ULS}$ (short-term extreme) or $MAEP/F_{ULS}$ (long-term extreme)

5 The Dual HIL testing platform

Starting from the specifications established in Section 3, the test rig design activities took place and developed into a final setup including all aspects related to mechanical, electrical and signal processing capabilities.

5.1 Drivetrain test rig

The design of the drivetrain test rig was based on knowledge and infrastructure previously developed in the project *IMAGINE: Innovative Method for Affordable Generation IN ocean Energy*[12]. That project aimed at developing the Electro-Mechanical Generator (EMG), an innovative linear PTO based on two parallelized systems that combine ball screws and permanent magnet generators.

The IMAGINE rig integrated:

- *generating unit*. a device made up of a ball screw and a permanent magnet synchronous machine; the unit can work both as a generator and as an actuator.
- *EMG*. Made up of two parallelized generating units working in unison and connected to the same moving carriage.
- *Power conversion system* . A drive unit managing a permanent magnet synchronous machine.
- *Control and monitoring system*. To implement control strategies at the power conversion system, it also integrates the real-time simulator to perform Hardware-In-the-Loop tests, the human-machine interface and the software to manage an ensure the safety of the rig operation.
- *Brake resistor*. To stop the operation of the rig in the shortest time possible following the detection of a critical fault.
- *A supply unit*. Allowing power circulation, the energy supplied to the drive units is equal to the inefficiencies of the overall conversion system (mechanical and electrical).

5.1.1 Summary of the requirements

The design of the IMPACT drivetrain test rig followed the main requirements previously identified, namely:

- Be able to host either rotary or linear PTOs.
- Have a rated power of 100kW and a peak power of 250kW.
- Integrate a flexible setup, allowing the adaptation of the maximum power point for various combinations between linear speed–force or rotational speed–torque.
- Allow dedicated tests for each key subsystem of the drivetrain (e.g. PTO, electrical power converter, control software, storage system, grid interface unit).
- Provide a simulated grid connection to assess the behaviour of the drivetrain with respect to different grid conditions.
- Allow HIL testing, to emulate the interaction of the drivetrain under test with the rest of the WEC.
- Address reliability tests to define the key aspects (e.g. failure modes and rates).
- Be designed according to input requirements identified by the Consortium and WEC developers belonging to the IMPACT's Technical Advisory Board (TAB), to address real case studies.

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[12] https://h2020-imagine.eu/

5.1.2 Architecture

The rig is targeting the whole drivetrain of a wave energy converter: a conversion chain from the mechanical input to the grid-compliant electrical output. It includes:

- Mechanical drives: gearbox, ball / roller / lead screw, rack-pinion, belt-pulley.
- Electrical generators.
- Power converters.
- Storage systems.
- Grid-interface units.
- Control system.

The functional block diagrams of the rig are shown in Figure 11 and Figure 12 for the ac and dc configurations, respectively. The rig can test drivetrains for off-grid WECs with the dc configuration, while the ac configuration targets grid-connected WECs.

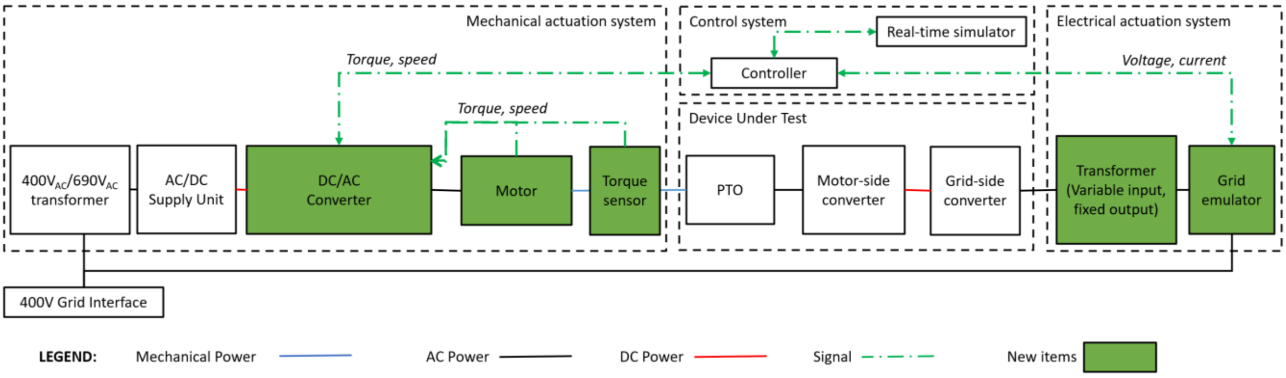

Figure 11 Drivetrain test rig ac architecture (not all transducers are represented).

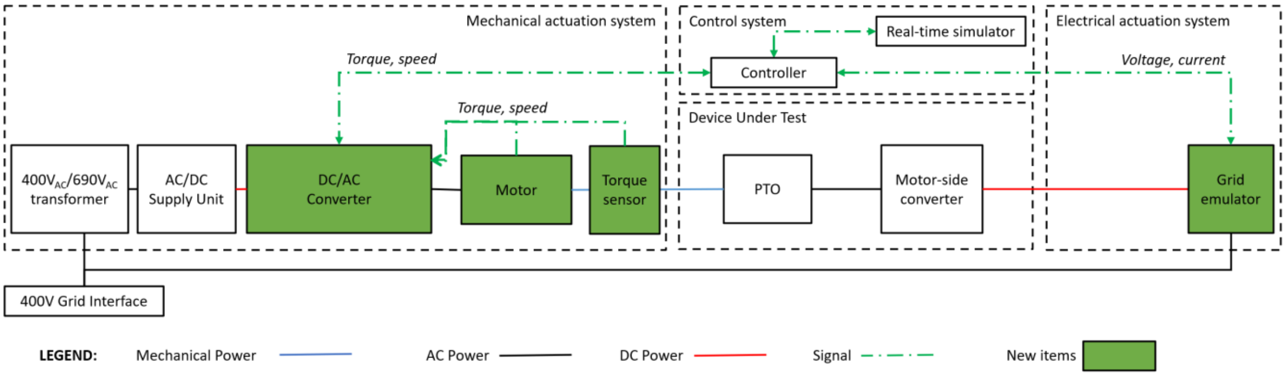

Figure 12 Drivetrain test rig dc architecture (not all transducers are represented).

5.1.3 Testing capabilities

The drivetrain test rig can perform the entirety, or part, of the following types of tests:

- Characterization (frictions, efficiency).
- Endurance.
- Accelerated tests.

- HIL tests.
- Dual HIL tests (when in combination with the IMPACT structural components test rig).

With respect to the objectives and methodologies presented in Sections 3 and 4, the drivetrain test rig design is capable of addressing these tests as per Table 8.

Table 8 Approaches to carry out tests under targeting different evaluation areas.

Type of test	Approach
Performance	• The definition of typical characterization profiles for mechanical (constant speed for basic testing and HIL for advanced testing) and electrical (normal grid conditions) interfaces. • Limited latency, allowing the execution of real-time simulation models within times compatible with ones currently used in similar applications. • Measuring mechanical (through torque transducer and encoder) and electrical data (through the grid emulator) at the interfaces with the DUT.
Reliability	• The definition of accelerated test profiles, either in position-, speed- or load-controlled mode. The rig allows the increase of load, frequency or displacement as acceleration factors. • Application of environmental condition proxies though the use of focused wave group or regular wave conditions. • Monitoring of the system degradation during time. Transducers may indicate consequence of degradation effects such as the increase of friction and the reduction of efficiency.
Survivability	• Characterization of DUT mechanical properties (e.g. stiffness) using load-controlled tests. • The definition of survivability loading profiles for mechanical (according to a pre-defined value or to a HIL simulation) and electrical (fault or abnormal grid conditions) interfaces. • Measurement of structural and electrical loads on the DUT during the tests. • Measurement of the performances of the device after the test, to find out eventual alterations due to permanent damages.

5.1.4 Specifications

The drivetrain test rig nameplate data is summarized in Table 9. Most of the parameters are referred to rotary units since linear PTOs could be tested with two different approaches: a) Using the linear actuation system already installed on the rig (with maximum speed up to 1m/s, maximum load up to 150kN); b) using a mechanical system for adapting the maximum power point of the actuator to the DUT speed-torque curve.

Table 9 Drivetrain test rig mechanical nameplate data.

Mechanical parameter	Unit	Rated	Max
Input power (direct connection)	kW	180	290
Input power* (adapted connection)	kW	160	250
Torque (direct connection)	Nm	5200	8400
Speed (direct connection)	rpm	330	680
Linear stroke	mm	4000	4250

* using mechanical components (e.g. gearbox/ballscrew) for adapting maximum power point of actuation system to the DUT speed–load curve.

The key electrical parameters of the test rig are summarized in Table 10.

Table 10 Drivetrain test rig key electrical nameplate data.

Electrical parameter	Unit	Ac	Dc
Output power (direct connection)	kVA	165	165
RMS voltage (direct connection)	V	606 (ph-ph)	990
RMS current (direct connection)	A	330 (ph-ph)	990
RMS voltage*(adapted connection)	V	871 (ph-ph)	N/A

* using the transformer with the highest conversion step

5.1.5 Assembly

The drivetrain test rig simplified design is presented in Figure 13, where the linear and rotary actuations systems can be seen. Moreover, the area for installing the PTO is indicated.

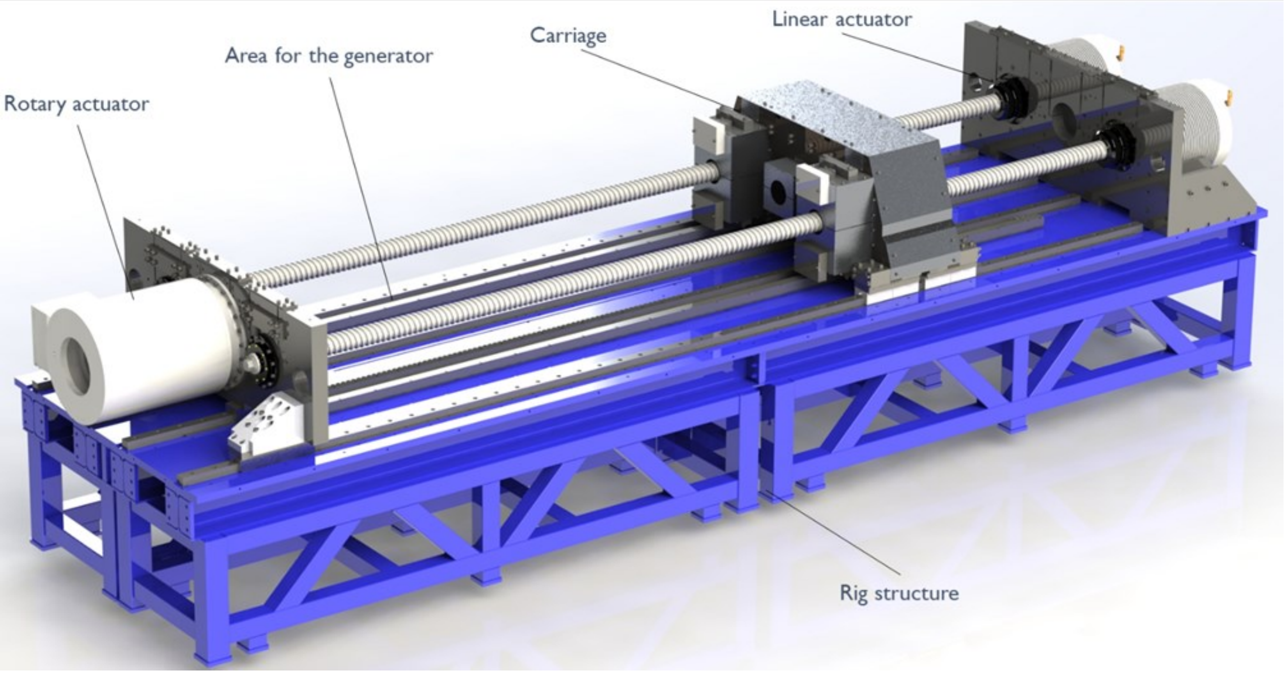

Figure 13 3D simplified view of the linear and rotary actuators installed on the drivetrain test rig.

An additional flexibility in terms of generator mounting arrangement was incorporated in the final assembly (not part of the initial requirements) to allow the motor to be connected not only to the fixed flange, but also in different areas of the rig. Figure 14 shows a 3D model with the motor mounted on the inside of the rig, on the central and side rails. A photo of the rotary motor (connected to a generator) on the rig is shown in Figure 15.

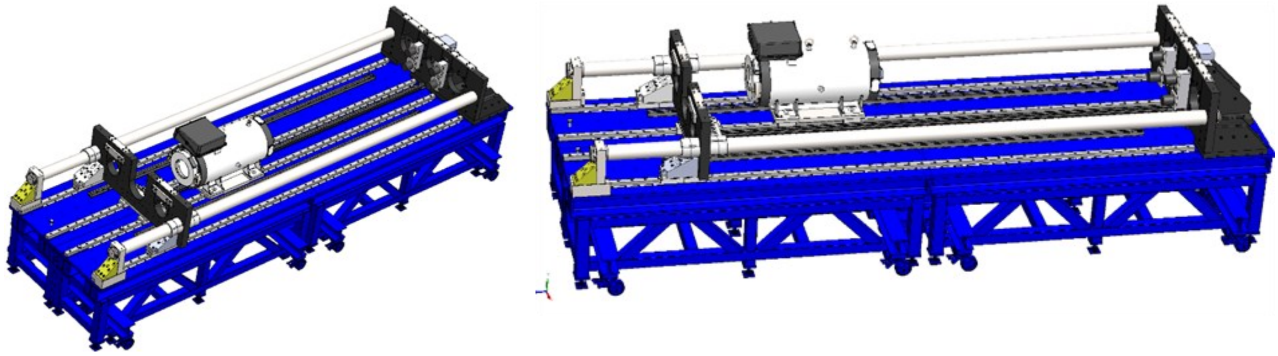

Figure 14 Rotary motor mounted inside the rig: on the central rails (left) and on side rails (right).

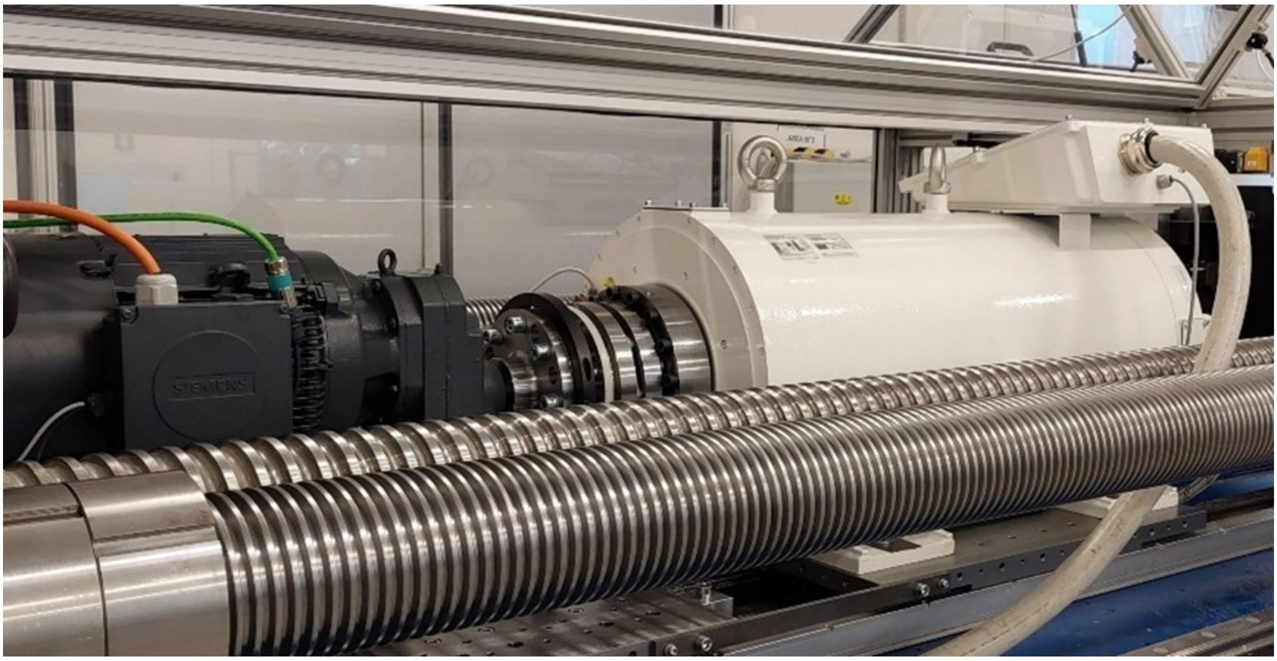

Figure 15 The actuating motor (machine on right-side) connected to a geared generator on the drivetrain test rig at VGA facilities.

5.2 Structural components test rig

The structural components test rig was designed to be capable of addressing performance, reliability and survivability tests, following the requirements and methodologies expressed in Sections 3 and 4, and to be able to measure the raw data which are at the base of the calculations for relevant metrics identified in Section 4.

5.2.1 Summary of the requirements

The design of the IMPACT structural components test rig followed the main requirements previously identified, namely:

- Integrate two actuation systems, allowing to replicate the required loads at the sample interfaces.
- Be capable of hosting test samples like structures of WECs, mechanical interfaces and mooring lines.
- Enable endurance testing, to reach the component fatigue limits (>10^6 cycles).
- Allow accelerated testing, reducing the test time by 50% with respect to typical endurance tests.
- Enabling the submerged testing with the use of "Synthetic Seawater" (per ASTM D1141-98).
- Allow HIL testing, to emulate the interaction of the component under test with the rest of the WEC.
- Address reliability tests to define the key aspects (e.g. failure modes and rates).
- Be designed according to input requirements identified by the Consortium and WEC developers belonging to the Technical Advisory Board (TAB), to address real case studies.

5.2.2 Architecture

The base architecture of the structural components test rig is presented in Figure 16 for a DUT interfaced to the full hydraulic actuation system integrating one linear actuator (called “main”) and two actuators as part of a gimbal joint, also called “multi-Degree Of Freedom (DOF) actuation system”.

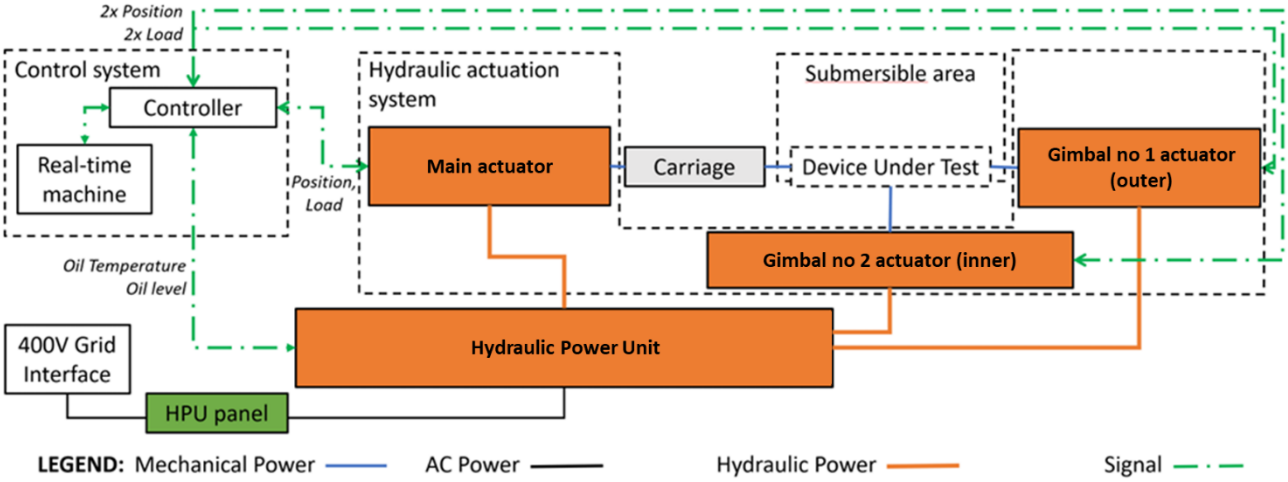

Figure 16 Structural components test rig architecture with full hydraulic system (not all transducers and auxiliaries are represented).

Figure 17 shows a different rig layout, which is used during the IMPACT demonstration campaign. In this context, the rig tests a belt as part of the mooring and power transmission system. It considered the initial layout of the rig and the required modifications (both in terms of actuation axes and equipment) to allow the test to take place. The presented layout includes an electro-mechanical actuation system, made up of a mechanically actuated trapezoidal screw (which applies a linear load on the DUT) and one rotary geared actuator (which puts the belt in rotation).

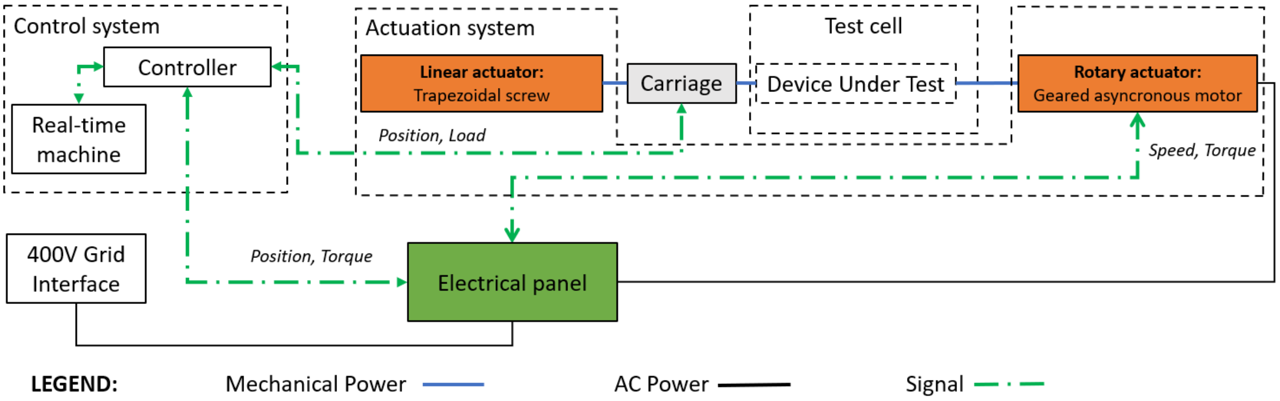

Figure 17 Structural components test rig architecture with electro-mechanical actuation system (not all transducers are represented).

5.2.3 Testing capabilities

The possible DUTs the structural components test rig can integrate are:

- Mechanical interfaces and (part of) structures.
- Mooring lines.
- Dynamic power cables.
- Dynamic seals.

The characteristics described above allow the test rig to conduct the following types of tests:

- Characterization (frictions, efficiency).
- Endurance.

- Accelerated tests.
- Hardware-In-the-Loop (HIL) tests.
- Dual HIL tests (when in combination with IMPACT drivetrain test rig).

The above list aims at covering the required activities before an open sea deployment campaign, either for a scaled prototype or a full-scaled commercial device (compatible with the described constraints).

5.2.4 Specifications

The structural components test rig nameplate data are summarized in Table 11.

Table 11 Structural components test rig mechanical nameplate data.

Mechanical parameter	Unit of measure	Value
Main actuator peak force	kN	800
Main actuator stroke	mm	500
2-DOFs system bending moment	kNm	10
2-DOFs system angular displacement	°	±40
Test cell inner size	mm	1450x1250x(h)2500

5.2.5 Assembly

The structural components test rig simplified design is presented in Figure 18, where the linear actuation system and water tank (required for tests with submerged DUTs) are shown. While they offer the interface of the test sample where the load is applied, the area for constraining the other interface of the test sample is indicated as “test cell”. A photo of the rig after the base assembly phase is show in Figure 19.

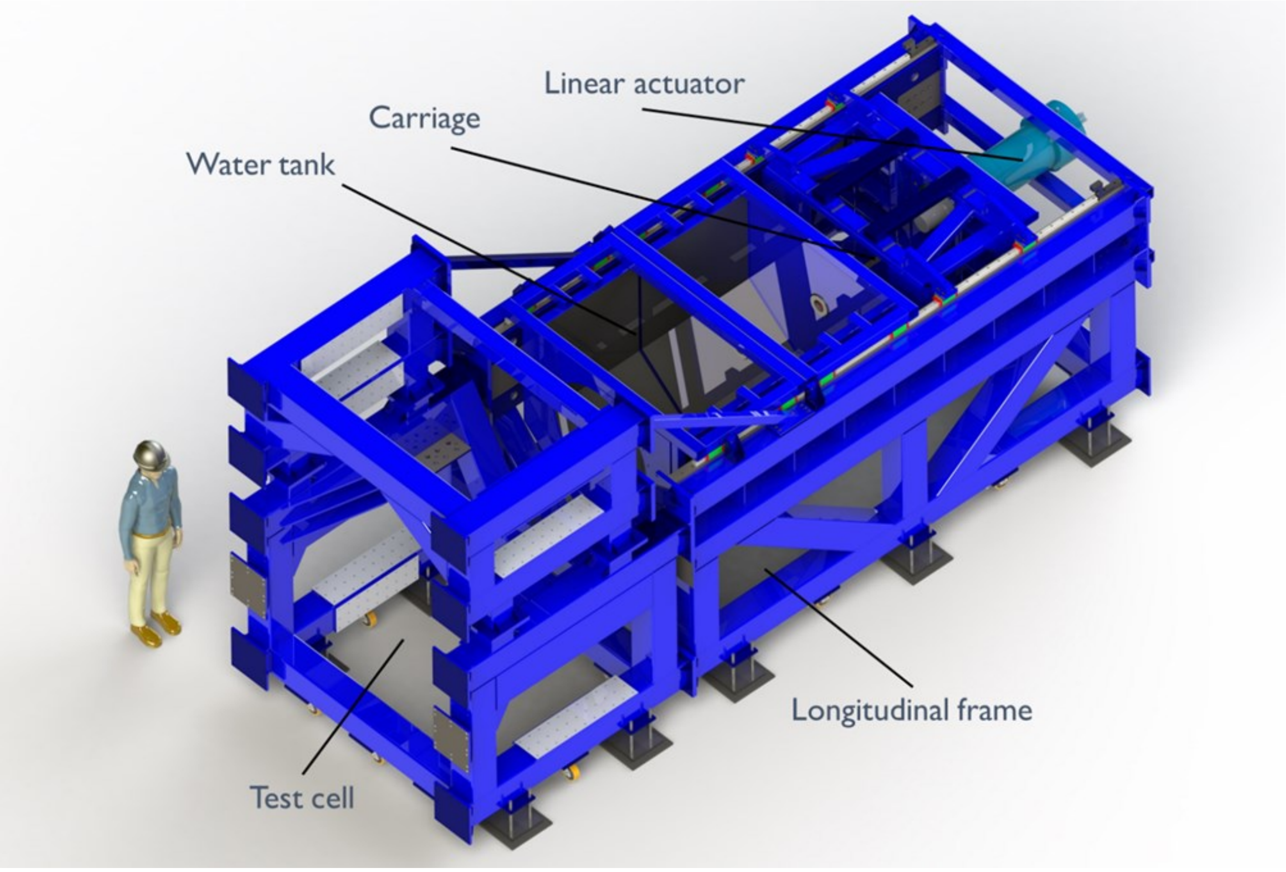

Figure 18 3D simplified view of the structural components test rig equipped with linear actuator and water tank.

Figure 19 Front view of the structural components test rig at the end of the (base) assembly phase.

Different loading profiles can be applied to the DUT by installing two additional linear actuators, connected to a gimbal joint. Figure 20 and Figure 21 show this setup, including the Hydraulic Power Unit (HPU) required to run all the linear actuators. Using other available interfaces of the test cell and dedicated test equipment, these actuators can also be mounted in other arrangements, allowing the application of radial loads and torque in different directions. Flexibility towards different lengths of test sample is accomplished by slots on each inner side of the longitudinal frame, allowing different positions of the frame integrating the carriage that can vary from 0.5m up to 3.0m in offset approximately. Figure 22 shows the closest and furthest frame positions, which guarantee an increase of about 2.5m in axial length (in addition to the approx. 3.0m already available within the test cell).

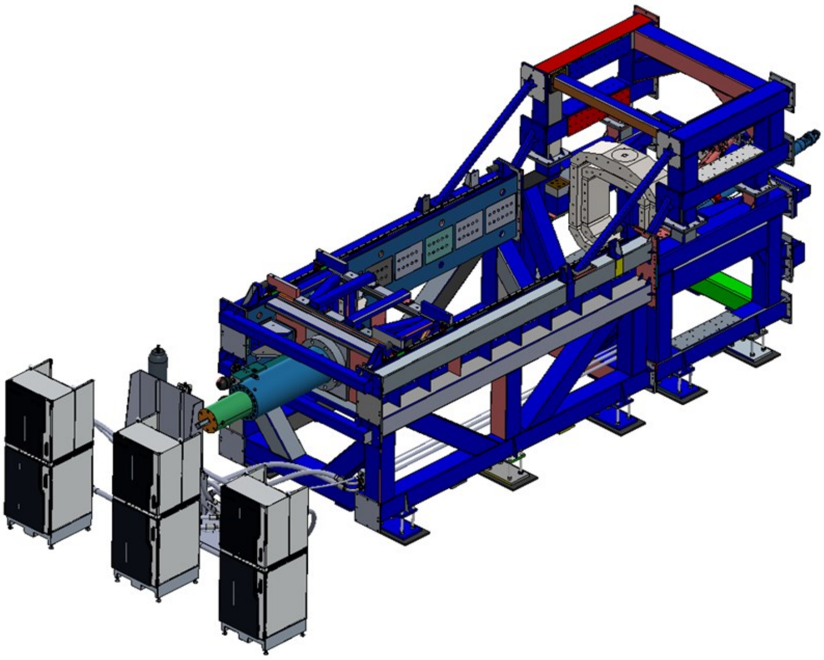

Figure 20 Front view of the structural components test rig with (from left): HPU, main actuator, carriage frame and gimbal joint.

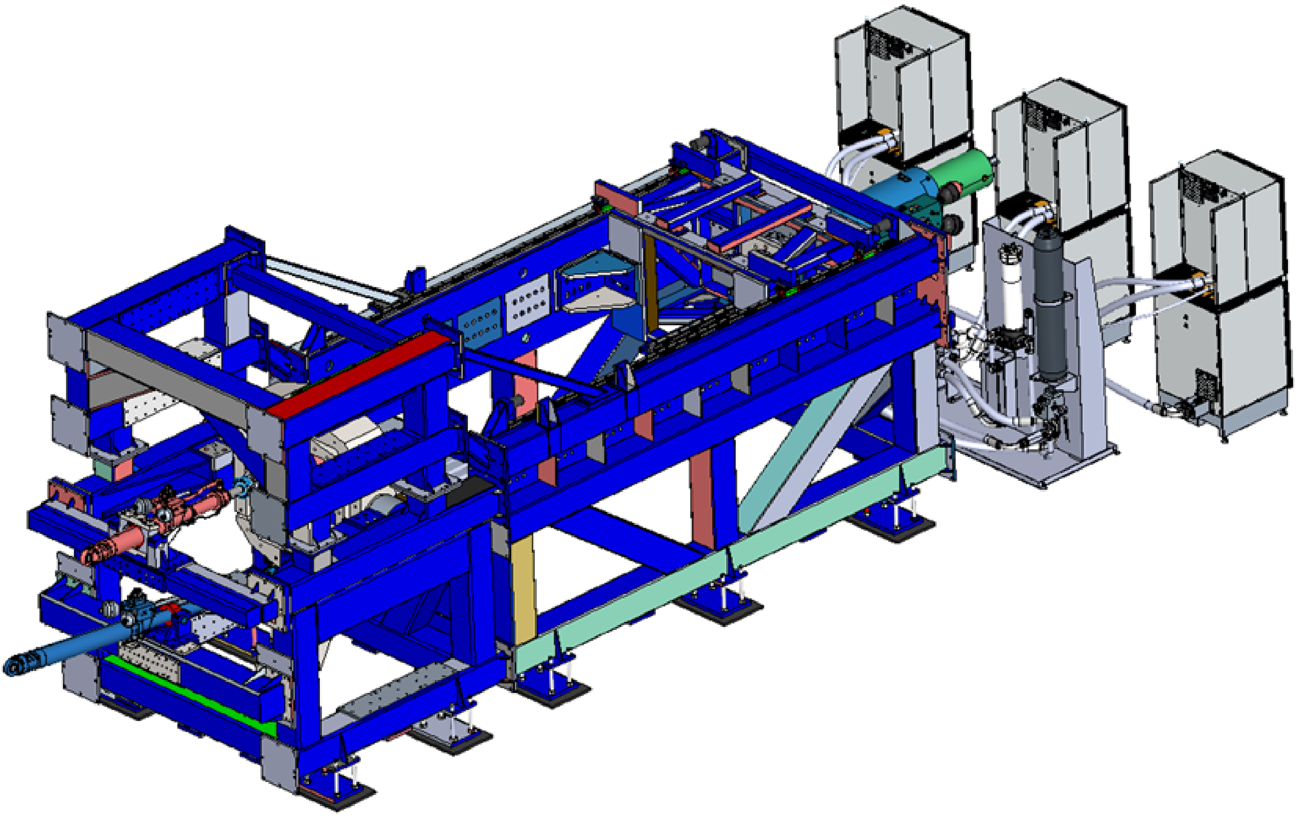

Figure 21 Back view of the structural components test rig with (from left): gimbal actuators, carriage frame and HPU.

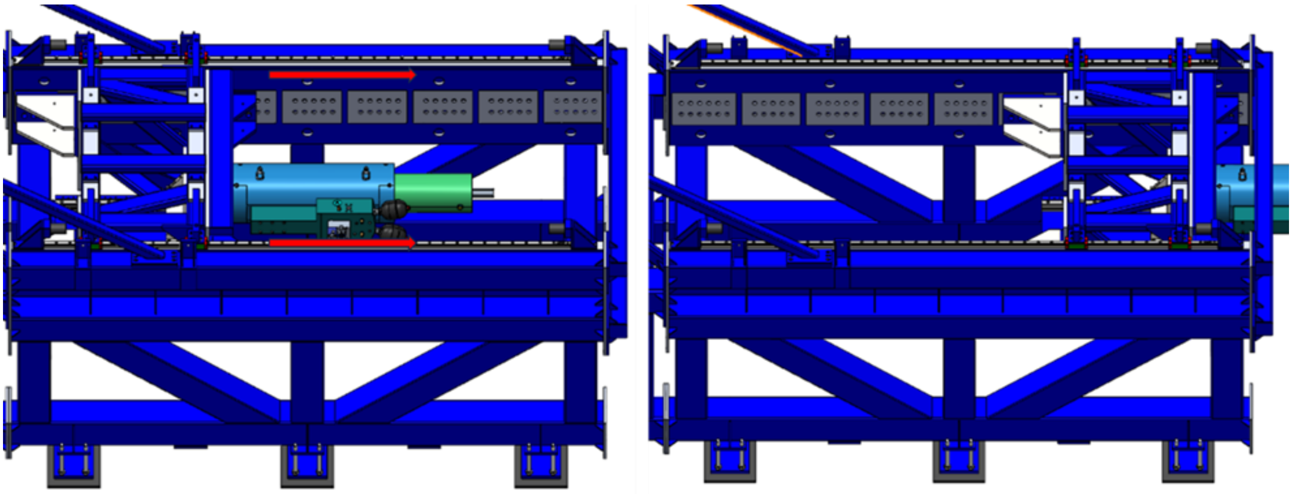

Figure 22 Closest (left) and furthers (right) carriage frame positions with respect to the test cell of structural components rig.

5.3 Capabilities for implementation of testing methodologies on each rig

The main functionalities of both rigs were verified during the commissioning phase, confirming the axes required within the IMPACT demonstration campaign can be successfully actuated.

Furthermore, the set of unit and integration tests allowed to verify how the drivetrain and structural components test rigs can, in line with objectives and methodologies presented in Sections 3 and 4, address:

- Performance tests, through the definition of typical characterization profiles, measuring mechanical (through torque/force transducers and encoders) and electrical data (through current and voltage transducers) at DUT interface. These can be used for defining:

- Material properties, such as using load-controlled actuation to define stiffness.
  - Mechanical properties, such as constant speed actuation for dynamic frictions.
  - Electrical characteristics, such as drivetrain response during normal grid conditions.
- Reliability tests, through the definition of accelerated test profiles, either in position- or load-controlled mode. Both rigs allow the increase of load, frequency or displacement as acceleration factors. In addition, transducers allow to monitor eventual changes on the system during time because of degradation effects, such as the increase of friction, decrease of efficiency and the variation of stiffness. These can be used for defining:
  - Failure modes, investigating how changing of parameters affected the damage on test sample.
  - Mean time to failures, using average failure time of different tested samples.
- Survivability tests, through verification of the DUT behaviour during application of survival loading profiles to mechanical (according to a pre-defined value or to a HIL simulation) and electrical (fault or abnormal grid conditions) interfaces. Measurement of structural and electrical loads applied to the DUT during the tests can allow to model its response and to verify the performances before and after the test, allowing to find out eventual alterations due to permanent damages. The tests can be used to:
  - Determine the design conditions boundaries beyond which a loss of functionality may occur.
  - Effectively verify how the system is behaving after the functionality is lost, to associate a severity level to each damage.

5.4 Architecture of the Dual HIL

The architecture of the Dual HIL testing platform is presented in Figure 23. The Real-Time (RT) machine is interfaced to the controllers of both rigs and able to send mechanical and electrical actuation inputs. This way, up of eight axes could be simultaneously managed on the two rigs: three on the drivetrain rig (one linear and two rotary actuators) and five on the structural components rig (three linear and two rotary actuators). Figure 23 specifically shows the architecture used for the demonstration campaign, adopting one rotary actuator on the drivetrain rig (i.e. for testing a rotary drivetrain) and one linear actuator plus one rotary actuation system.

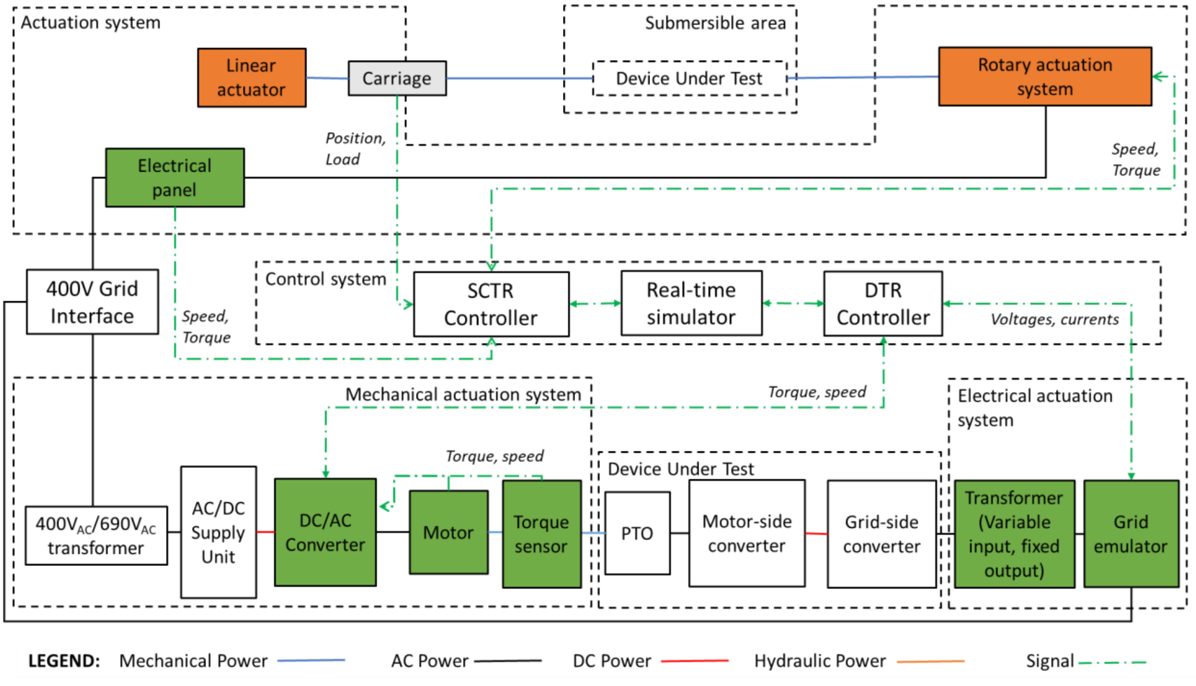

Figure 23 Dual HIL testing platform architecture.

Figure 24 shows all the possible communication interfaces that can be involved within the Dual HIL testing platform. The PLC managing the drives installed on the electrical cabinet of the drivetrain rig is interfaced to the EtherCAT slave board n.1 of the RT simulator, while the hydraulic system is connected to the EtherCAT slave board n.2. The grid emulator and the PLC of the rotary motor are instead interfaced to the same analog board.

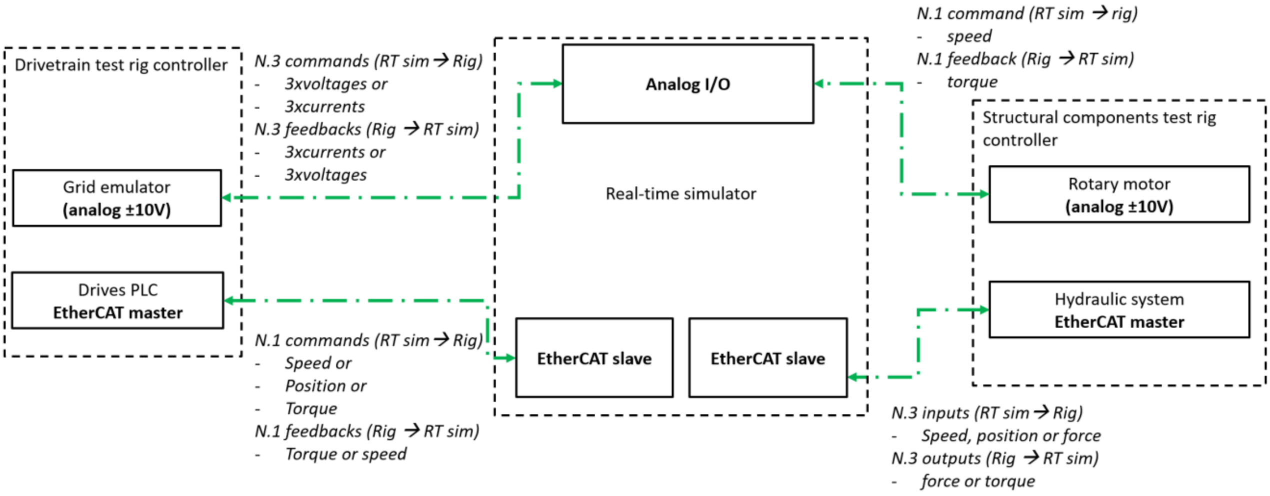

Figure 24 Dual HIL testing platform communication interfaces.

5.5 Digital Twin Models and public IoT framework

Remote monitoring of the tests was enabled by using Digital Twin models and a public domain based IoT framework for visualization of measured and simulated data, shown in Figure 25. The data can be used to add event triggers capturing deviations from normal operations and loads. The event triggers can in turn be used to invoke alarms indication failure modes and to reduce the amount of stored data from tests and simulations.

Focused on Structural Health Monitoring (SHM), the digital twins of the test rigs are represented by a Component Mode Synthesis (CMS) reduced assembly FEM applicable to real time execution. The Finite Element (FE) simulation model can be exported as a Digital Twin model through a Functional Mockup Unit (FMU) to the digital framework for HIL and Dual HIL simulations. The simulation model is also used to generate a Reduced Order Model (ROM). A digital framework can be configured to simultaneously execute and sample data from physical and virtual FMU/ROM sensors on the WEC test rig during tests.

The DT model can run in both real time and off-line mode. In real time mode, the physical test rig excitations are sampled and streamed to the digital twin model using open software solutions. Real-time stress and fatigue analysis for the selected load cases can be conducted using virtual strain gauges located at hot spots and identified by a virtual brittle lacquer technique. The streamed data is also buffered and stored on .CSV files for later digital twin off-line execution.

The IoT framework supporting data sampling, visualization, analytics, event handling, anomaly detection and digital twin execution is based on open-source Python[13] and Streamlit[14] scripts. The digital twin model is prepared and executed by the open-source software FEDEM[15] based on both live streaming and historical data. A new two-step FMU and ROM process was developed and applied for Dual HIL execution.

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[13] https://www.python.org/

[14] https://streamlit.io/

[15] https://openfedem.org/

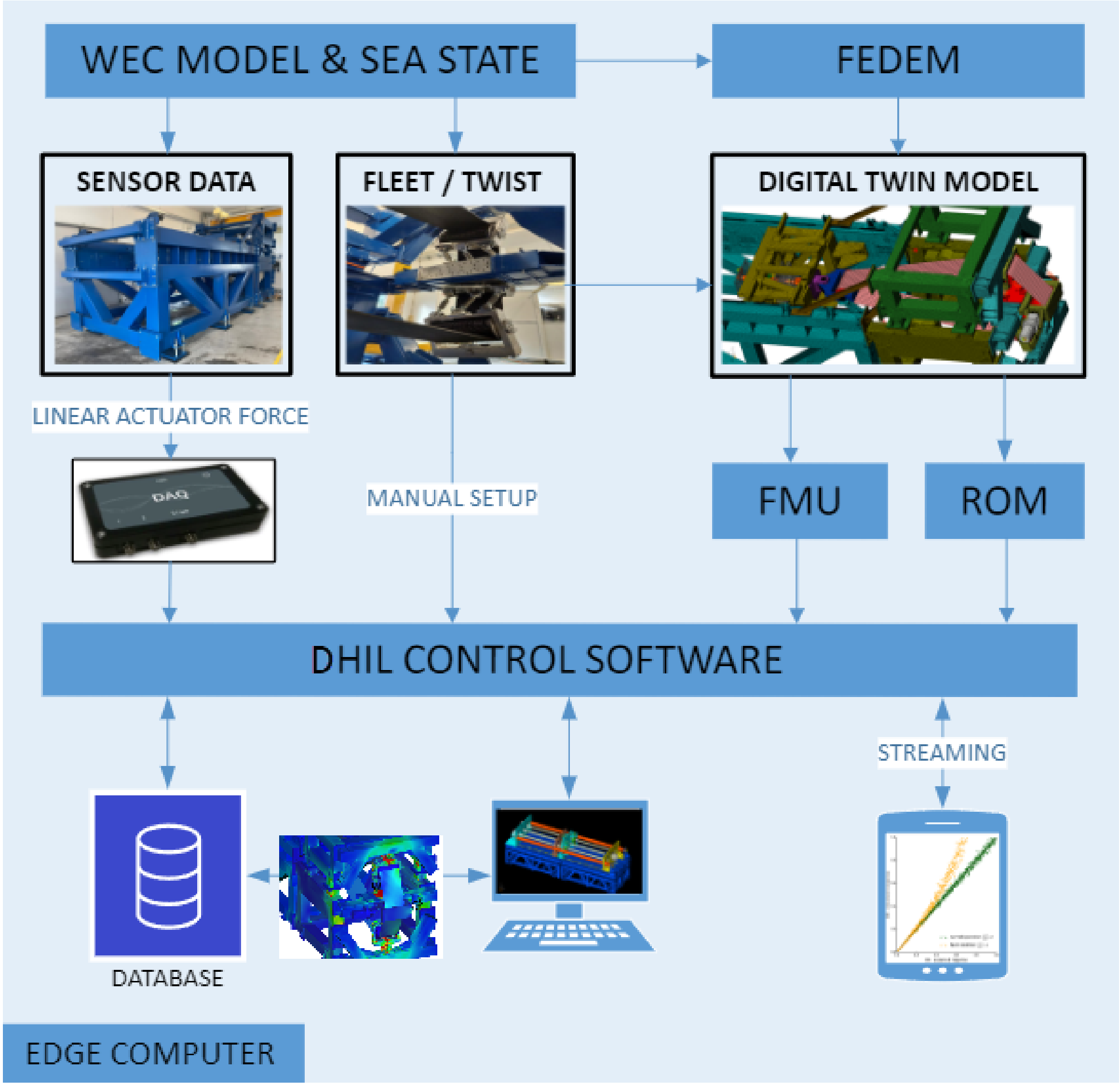


Figure 25 IoT framework for visualization of measured and simulated data.

6 Testing activities on the rigs

The current section aims at describing the activities carried out for the demonstration of the rigs' functionalities, by testing subsystems/components for wave energy applications. Section 6.1 provides details on the selection process of the DUTs; sections 6.2 and 6.3 describe the testing activities on the drivetrain and structural components test rig, respectively. Finally, section 6.4 provides an outline of the experimental activities carried out using the dual HIL testing platform.

6.1 Selection of devices / subsystems for testing

6.1.1 End-user engagement

With the objective to maximise the outreach of the project, foster the use of the IMPACT test rigs, and test methodologies in future test campaigns, the IMPACT consortium engaged with the wave energy sector at multiple stages of the project. Part of such engagement activities also aimed to identify and connect with potential test rig users within the framework of the IMPACT project.

In addition to this, Y4C conducted a market consultation exercise on behalf of the IMPACT consortium to assess the potential interest of a wider range of technology developers in the IMPACT test rigs and test methodologies. A total of 17 respondents of various backgrounds participated to the market consultation – which was conducted via an online survey. The vast majority of the respondents showed an interest in using the IMPACT rigs, as outlined in Figure 26, with PTO testing for power production related design situations being identified as the most sought-after subsystem and conditions for testing.

From this shortlist of potential end-users, Carnegie Clean Energy (CCE) demonstrated the greatest interest in becoming an early adopter of the IMPACT methodologies and user of the IMPACT test rigs, and detailed discussions followed.

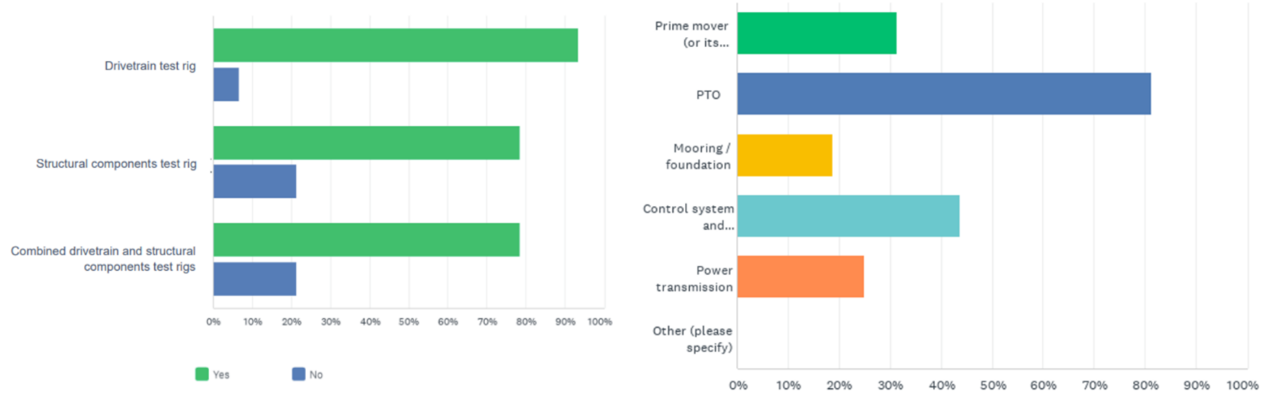


Figure 26 Left: Interest of the survey respondents in a potential use of the IMPACT test rigs. Right: Preferred subsystem to be considered in the IMPACT test rigs.

6.1.2 Risk assessment

In addition to the end-user engagement activities, a framework for assessing the risks associated with using the IMPACT test rigs was developed based, at a high-level, on three documents: ISO 31000:2018 *Risk management — Guidelines*; IEC 31010:2019 *Risk management — Risk assessment techniques*; and DNV-SE-0120 *Certification of wave energy converters and arrays*. An IMPACT risk matrix template was created documenting the associated risk(s), in both pre- and post-mitigation scenarios, defining the primary entity responsible for addressing such risks and the mitigation / improvement measures to apply (if applicable) – see Appendix B.

6.2 Drivetrain Rig Testing: Electrical Generator (Generic)

A PTO subsystem was selected (after an evaluation jointly conducted by the supplier and VGA) as user of the IMPACT drivetrain rig, however tests on this subsystem were not conducted due to timeline issues. Noting its similarities to the PTOs used in wave energy applications, the test component subsequently chosen for the drivetrain test campaign was a standard drivetrain based on a rotary electrical generator, provided by VGA. This involved the retrofitting of an existing system at the VGA facilities.

The generator selected for the demonstration campaign on the drivetrain test rig is a three-phase asynchronous machine connected to a gearbox with parallel shafts. Figure 27 shows a 3D view of the electrical generator tested on the drivetrain test rig. Table 12 lists the main generator characteristics.

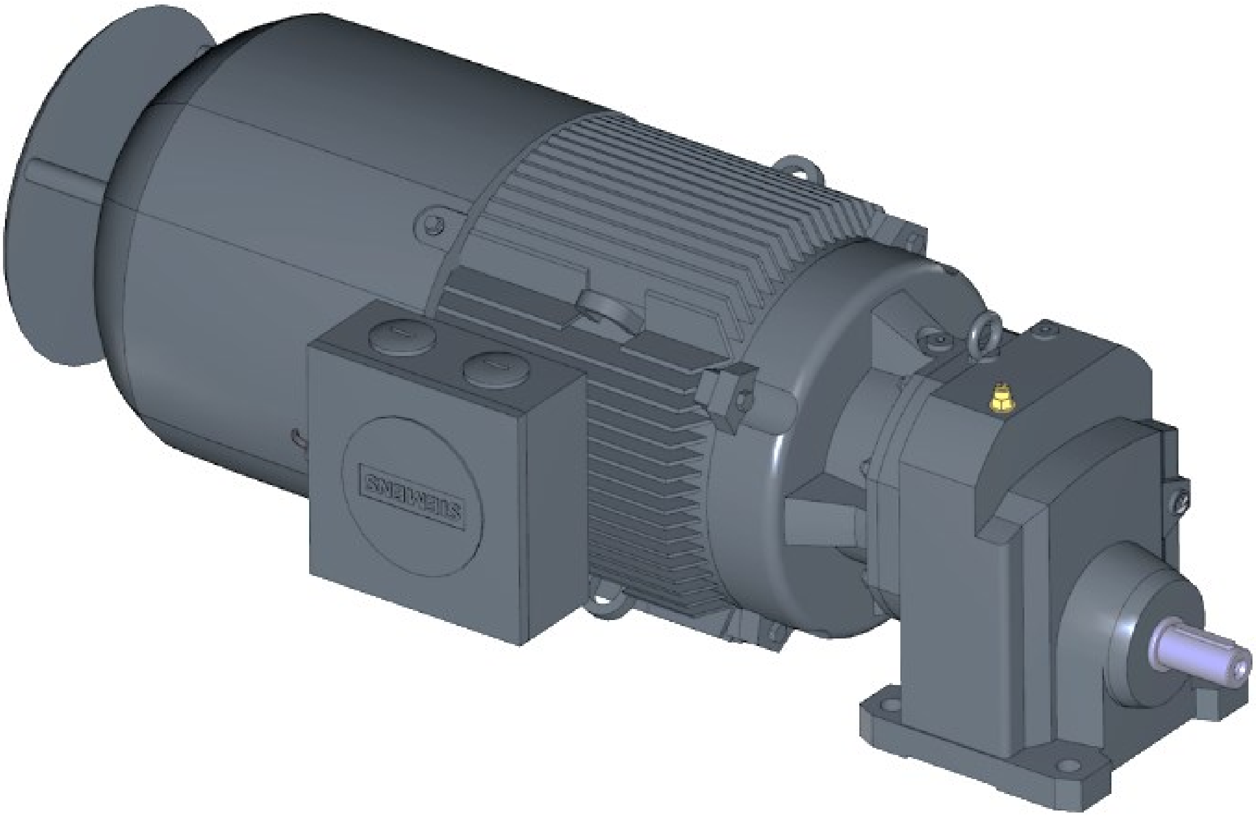


Figure 27 3D schematic view of the electrical generator.

Table 12 Characteristics of the generator.

Characteristic	Value	Unit of measure
Code n.	2KJ3003-1JQ23-9AD1-Z	-
N. poles	4	-
Inertia	0.071	$kg.m^2$
Weight	111.7	kg
Gear ratio	1:2.22	-
Output shaft key	50x8	mm
Shaft size	30	mm
Brake	Yes	-
Brake torque	150	Nm
Encoder code	(Q47) HTL1024S/R KD	-
Encoder	Incremental single turn	-
Pulses per turn	1024	-
Motor module power	12.9	kW

The speed-torque curves (rated and maximum values) of the generator are presented in Figure 28. These were provided by the supplier as the reference for the operational limits of the generator in terms of torque. The limit in terms of speed is given by the rig motor characteristics, equal to 650 RPM.

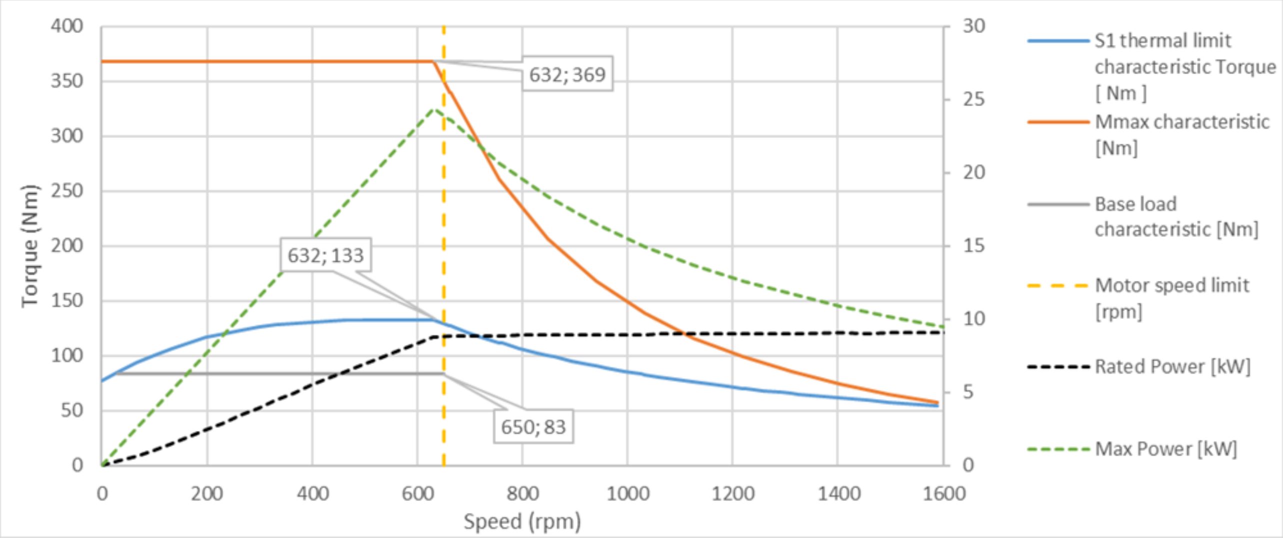


Figure 28 Speed-torque curves for generator and speed limit for the motor (yellow dashed line).

6.2.1 Test planning

In preparation for the generic electrical generator tests, a test documentation, in-line with the IMPACT methodology outlined in Section 4, was carried out. The test campaign consisted of two key test types on the generic electrical generator:

- Characterisation tests, including static friction, dynamic friction, inertia test, power consumption test, and efficiency tests. These tests aim to assess the overall capabilities of the electrical generator in non WEC-related test conditions. The tests also aim to demonstrate the capacity of the drivetrain test rig for a range of different characterisation related tests.
- HIL tests, aiming to demonstrate the ability of the drivetrain test rig to conduct HIL tests relevant to a WEC device. These tests aim to assess the overall efficiency of the electrical generator in WEC-related test conditions.

As a generic electrical generator is the test component, a WEC numerical model compatible with the generator was used to run HIL tests. Specifically, the SPD WEC numerical model (see Section 3.1) was adapted for this purpose including a conversion from linear to rotary motion and adaptation of the WEC model to HIL real-time model. This required e.g. the replacement of the PTO subsystem in the WEC model with the input / output structure required to run test, which in this specific case are the speed and torque, respectively. Table 13 presents the building blocks for the electrical generator testing campaign prepared by VGA.

Table 13 IMPACT methodology building blocks for the electrical generator testing campaign.

Foundation block	Functional block	Input block	Outline description
Pre-processing	Test conditions	Environmental conditions	Reduced normal sea state (RNSS) related to one of the sites indicated in WP2
		WEC status	Power production (DLC1,1).
	Test set-up	Testing strategy	HIL

Foundation block	Functional block	Input block	Outline description
		Scaling assessment	Scale factor of 10, based on WEC numerical model vs. generator capabilities.
		Target machine set-up	Model updated with interface connection to actuation system. HIL connection with drivetrain test rig (EtherCAT): input signal in speed, feedback in torque.
	Rig set-up	Hardware set-up	Rotary actuator managed by the PLC of rig control panel. Other drives are OFF. Standard grid connection.
		Preliminary rig test	Actuation of the motor by the HMI replicating profiles to be used in basic testing. Actuation of the motor by RT machine replicating profiles for advanced testing (open loop).
Processing	DUT & transducers installation	DUT installation	Geared generator installed on rig and connected to the torque sensor (by means of a dedicated adapter). Drivetrain (geared generator + AC/DC drive + DC/AC drive) connected to grid.
		DAQ system set-up	Rotary encoders (n.1 for motor rotation, n.1 for generator rotation). Torque sensor (including speed). Thermal gauges embedded in the motor. Thermal gauge on the gearbox of the generator. Voltage and current sensors installed at generator outputs.
	Basic testing	Signal tests	Run-in of motor (at constant speed) without load from generator (excluding mechanical frictions): - signals from transducers are acquired - Eventual misalignments to be checked
		DUT model calibration	Ensuring the DUT can apply load, according to a certain control mathematical function (e.g. pure damping).
		DUT characterisation	Tests to define the DUT model: - static frictions (DUT OFF): increasing load applied up to generator rotation (at low acceleration) - dynamic frictions (DUT OFF): fixed speed applied to generator axis (at different constant speeds) - inertia tests (DUT OFF): increasing start-up acceleration - power consumption (DUT ON): measurement of current absorbed when no load is applied on shaft - efficiency characterization (DUT ON): measurements at fixed speed within the generator operational envelope
	Advanced testing	DLC 1.1 test programme	Performance characterization of the PTO.
		Signal monitoring (DUT and rig)	Torque, speed, absorbed currents and voltages (AC and DC), motor and generator temperatures.
Post-processing	Inspection	DUT status	Visual inspection.
		Rig status	Visual inspection.
	Data quality	Data quality check	Eventual data duplicates, missing data, outliers.

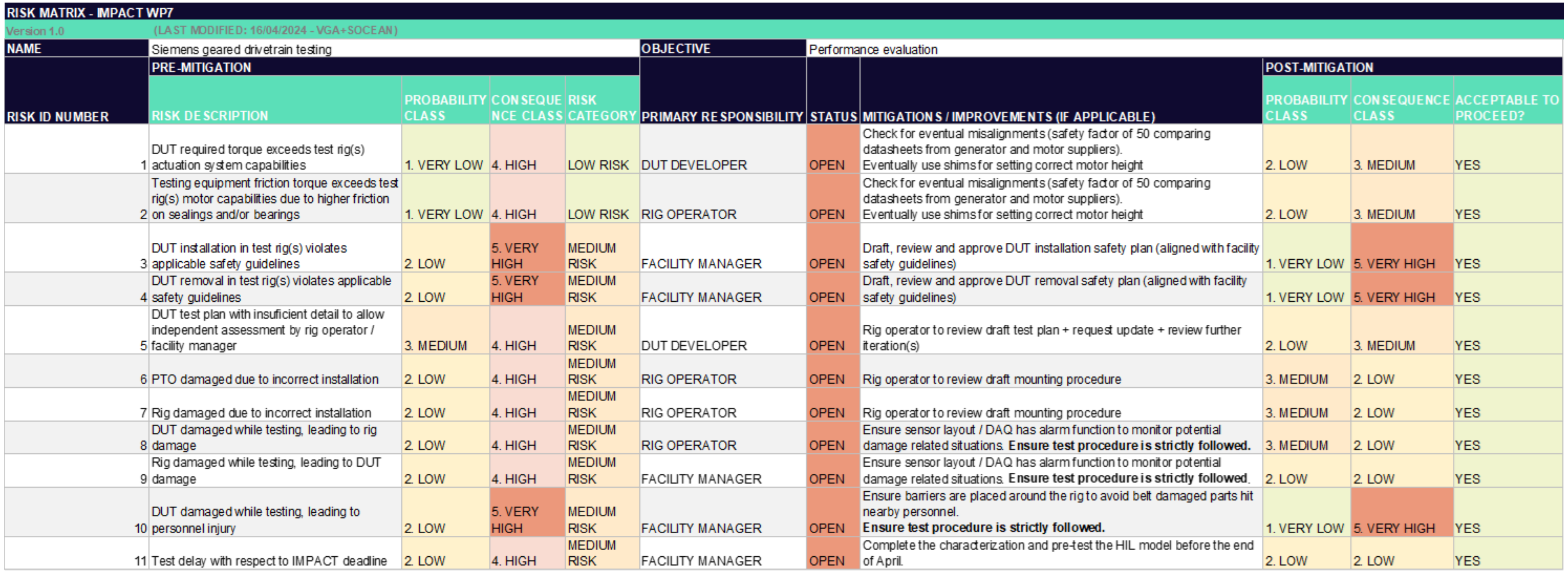
Foundation block	**Functional block**	**Input block**	**Outline description**
		Raw data filtering	Eventual electro-magnetic noise, vibration.
	Data analysis and reporting	Metrics assessment	Performance metrics: power conversion efficiency across RNSS.
		Uncertainty assessment	Consider setup, measurement and analysis errors.
		Reporting	Characterization and performance-driven.

Theoretical	**Numerical**	**Experimental**

6.2.2 Risk assessment

Following the IMPACT risk assessment framework – see Section 6.1.2 – and using the risk matrix template illustrated in Appendix B, a risk matrix specific to the generic generator test plan was developed by VGA. The resulting matrix is illustrated in Figure 29.

A total of eleven risks were identified; two of the identified risks were assigned to the DUT developer, five to the facility manager and four to the rig operator. At the risk pre-mitigation status, two of the identified risks were characterised as 'low' risk, with the remaining one being identified as a 'medium' risk. Following the methodology detailed in Section 6.1.2, at post-mitigation level all the risks were deemed as acceptable to proceed with the tests.



RISK MATRIX - IMPACT WP7
Version 1.0 (LAST MODIFIED: 16/04/2024 - VGA+SOCEAN)
NAME: Siemens geared drivetrain testing
OBJECTIVE: Performance evaluation

	PRE-MITIGATION							POST-MITIGATION		
RISK ID NUMBER	RISK DESCRIPTION	PROBABILITY CLASS	CONSEQUENCE CLASS	RISK CATEGORY	PRIMARY RESPONSIBILITY	STATUS	MITIGATIONS / IMPROVEMENTS (IF APPLICABLE)	PROBABILITY CLASS	CONSEQUENCE CLASS	ACCEPTABLE TO PROCEED?
1	DUT required torque exceeds test rig(s) actuation system capabilities	1. VERY LOW	4. HIGH	LOW RISK	DUT DEVELOPER	OPEN	Check for eventual misalignments (safety factor of 50 comparing datasheets from generator and motor suppliers). Eventually use shims for setting correct motor height	2. LOW	3. MEDIUM	YES
2	Testing equipment friction torque exceeds test rig(s) motor capabilities due to higher friction on sealings and/or bearings	1. VERY LOW	4. HIGH	LOW RISK	RIG OPERATOR	OPEN	Check for eventual misalignments (safety factor of 50 comparing datasheets from generator and motor suppliers). Eventually use shims for setting correct motor height	2. LOW	3. MEDIUM	YES
3	DUT installation in test rig(s) violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT installation safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
4	DUT removal in test rig(s) violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT removal safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
5	DUT test plan with insuficient detail to allow independent assessment by rig operator / facility manager	3. MEDIUM	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	Rig operator to review draft test plan + request update + review further iteration(s)	2. LOW	3. MEDIUM	YES
6	PTO damaged due to incorrect installation	2. LOW	4. HIGH	MEDIUM RISK	RIG OPERATOR	OPEN	Rig operator to review draft mounting procedure	3. MEDIUM	2. LOW	YES
7	Rig damaged due to incorrect installation	2. LOW	4. HIGH	MEDIUM RISK	RIG OPERATOR	OPEN	Rig operator to review draft mounting procedure	3. MEDIUM	2. LOW	YES
8	DUT damaged while testing, leading to rig damage	2. LOW	4. HIGH	MEDIUM RISK	RIG OPERATOR	OPEN	Ensure sensor layout / DAQ has alarm function to monitor potential damage related situations. **Ensure test procedure is strictly followed.**	3. MEDIUM	2. LOW	YES
9	Rig damaged while testing, leading to DUT damage	2. LOW	4. HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Ensure sensor layout / DAQ has alarm function to monitor potential damage related situations. **Ensure test procedure is strictly followed**.	2. LOW	2. LOW	YES
10	DUT damaged while testing, leading to personnel injury	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Ensure barriers are placed around the rig to avoid belt damaged parts hit nearby personnel. **Ensure test procedure is strictly followed.**	1. VERY LOW	5. VERY HIGH	YES
11	Test delay with respect to IMPACT deadline	2. LOW	4. HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Complete the characterization and pre-test the HIL model before the end of April.	2. LOW	2. LOW	YES

Figure 29 Risk matrix – Drivetrain electrical generator (generic) test plan.

6.2.3 Test setup

Figure 30 and Figure 31 illustrate a graphic of the generator setup on the drivetrain test rig and its photographs, respectively.

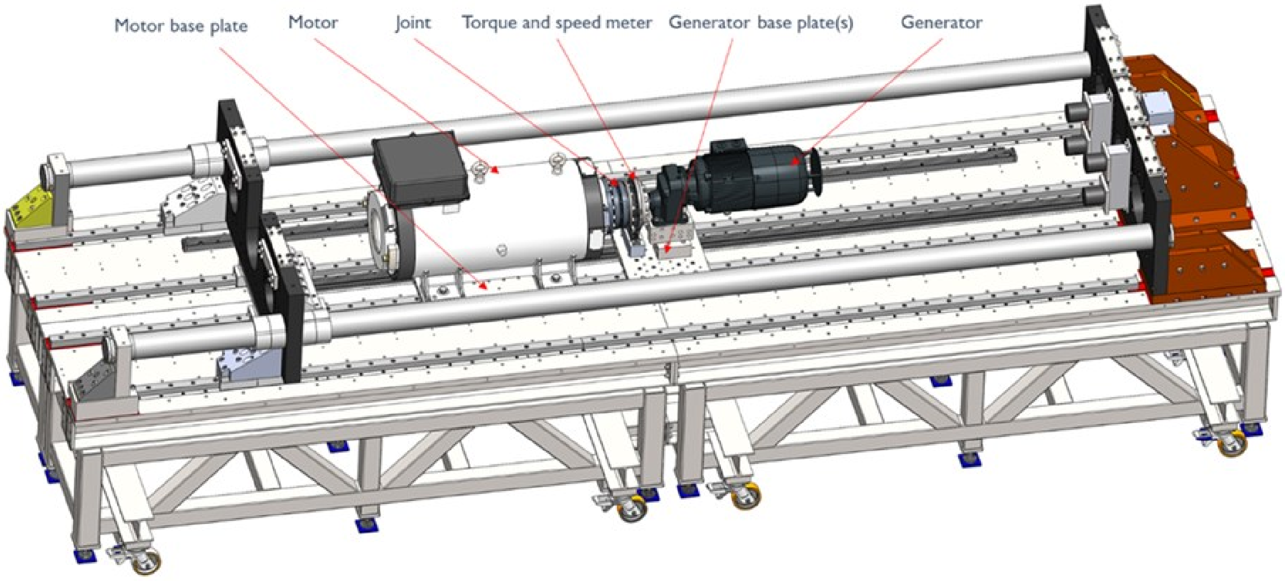


Figure 30 Rig setup for the drivetrain tests.

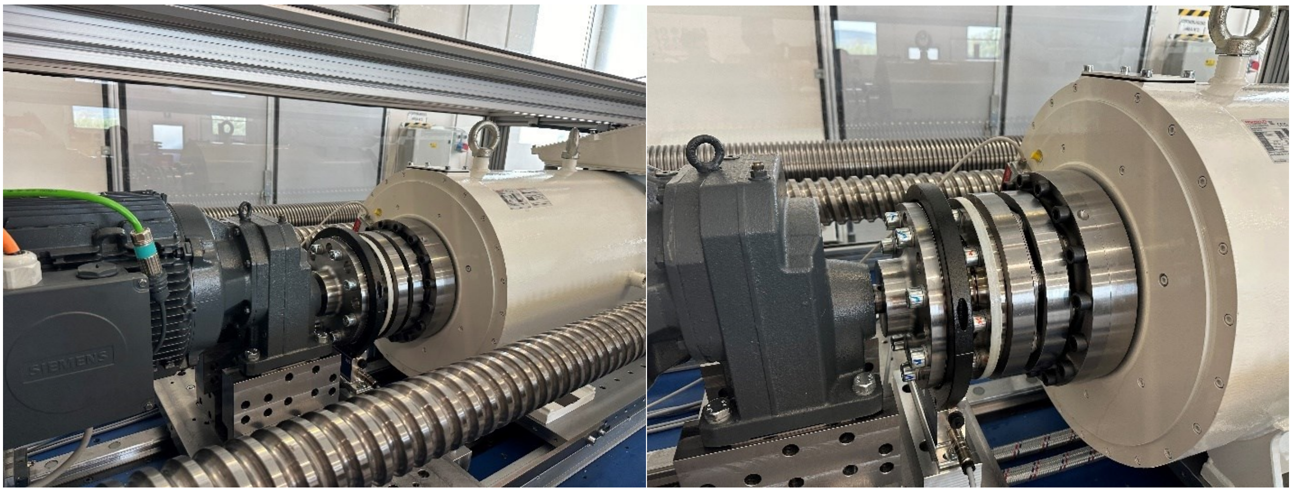


Figure 31 From left side: generator, torque transducer, backlash-free shaft coupling and rotary actuator (motor) with respective support plates and rails, installed on the drivetrain test rig**.**

6.2.4 Test execution

An overview of the tests conducted on the drivetrain test rig is provided in what follows.

<u>DUT Characterisation Tests</u>

The drivetrain characterisation tests programme comprised of:

- Static Friction, Dynamic Friction and Inertia Tests.
- Power Consumption Tests.
- Efficiency Characterisation Tests.

The suite of characterisation tests aimed to define the mathematical equations that can be used to model the behaviour of the drivetrain, specifically of the geared generator.

Static Friction Tests. The aim of static friction tests was to define the torque required to overcome the mechanical frictions of the components inside the generator (considering the brake is not engaged). This situation shows up each time the motion of the input axis inverts its direction, and therefore is important to determine the torque value that is required to move the axis.

Dynamic Friction Tests. The aim of dynamic friction tests was to define the torque value required to keep the speed of the input shaft stable, which equals to overcome the dynamic mechanical frictions of the components inside the generator (considering the brake is not engaged). This situation shows up each time the input axis is moved (without considering inertial effect) and there is not electrical load applied. This case may cover very low-energy sea states or other non-operative cases (e.g. shut-down and maintenance), therefore is important to determine the torque value that is required at different speeds.

Inertia Tests The aim of inertia tests was to define the effective inertia value of the rotating components. This value is usually given by the supplier, but it is of interest to verify it through experimental data.

Power Consumption Tests The aim of power consumption tests was to define the power dissipated by the system when the generator is not working. This value may be given by the supplier, but it is of interest to verify it through experimental data.

Efficiency Characterisation Tests The aim of efficiency characterisation tests was to define the power generated by the system with respect to the input, when the whole drivetrain is working. This value may be given by the supplier, but it is of interest to verify it through experimental data.

Hardware-in-the-Loop Tests

The aim of endurance tests was to verify the capability of the drivetrain to work under representative wave-energy derived input conditions listed in Table 14.

Table 14 Electrical generator HIL test plan execution.

Test #	Type of spectrum	Hs (m)	Tp (s)	Seed	Ramp-up time (s)	Ramp-down time (s)	Overall test time (s)	PTO status	Damping (Nm/rpm)
1	Bretschneider	1.25	7	2	15	10	60	Active	0.25
2	Bretschneider	1.25	7	2	15	10	60	Active	0.5
3	Bretschneider	1.25	7	2	15	10	60	Active	0.75
4	Bretschneider	1.25	7	2	15	10	60	Active	1
5	Bretschneider	1.25	7	2	15	10	60	Active	1.25
6	Bretschneider	2.25	7	2	15	10	60	Active	0.25
7	Bretschneider	2.25	7	2	15	10	60	Active	0.5
8	Bretschneider	2.25	7	2	15	10	60	Active	0.75
9	Bretschneider	2.25	7	2	15	10	60	Active	1
10	Bretschneider	2.25	7	2	15	10	60	Active	1.25
11	Bretschneider	5.75	9	2	15	10	60	Active	0.25
12	Bretschneider	5.75	9	2	15	10	60	Active	0.5
13	Bretschneider	5.75	9	2	15	10	60	Active	0.75
14	Bretschneider	5.75	9	2	15	10	60	Active	1
15	Bretschneider	5.75	9	2	15	10	60	Active	1.25

6.2.5 Data post-processing and results

Following the generic principles of the IMPACT framework defined in Section 4, a range of post-processing activities were conducted following the completion of the drivetrain testing. As an illustrative example, an overview of the results from the DUT Characterisation Tests is provided in this subsection.

The characterisation tests aimed to assess the fundamental equations that can be used to model the drivetrain behaviour. Among these, the efficiency characterisation tests characterise the operational regime of the drivetrain, to experimentally verify the estimates provided by the supplier of the DUT.

Figure 32 illustrates some of the key results from the drivetrain efficiency characterisation tests. Firstly, the generator response is evaluated in terms of its efficiency as a function of speed, for several torque values (Figure 32, left). It can be observed that at higher / close to nominal rotational speed (632rpm), the generator efficiency asymptotically converges to similar values, as expected, with a small effect of the torque value on the resulting efficiency. Additionally, the relationship between torque and speed is of particular interest for wave energy application, and as illustrated in Figure 32 (right), for intermediate values of rotational speed such relationship is linear, with the inception of nonlinear regimes being more evident for the 0.5 and 0.75Nm/rpm PTO damping settings at around 250 and 500 RPM, respectively.

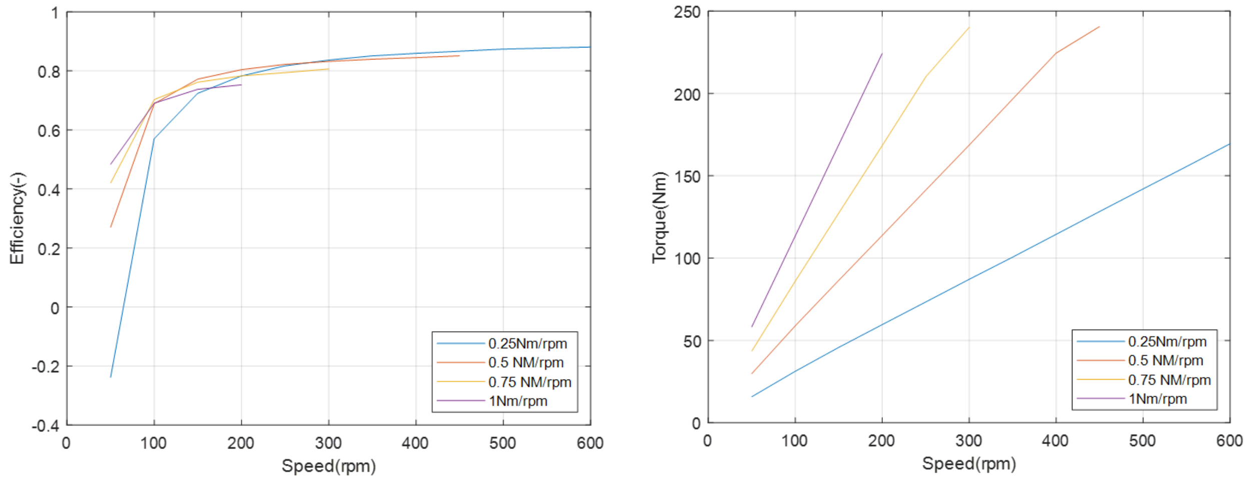


Figure 32 Key results from selected drivetrain efficiency characterization tests: speed vs. efficiency (left) and speed vs. torque (right).

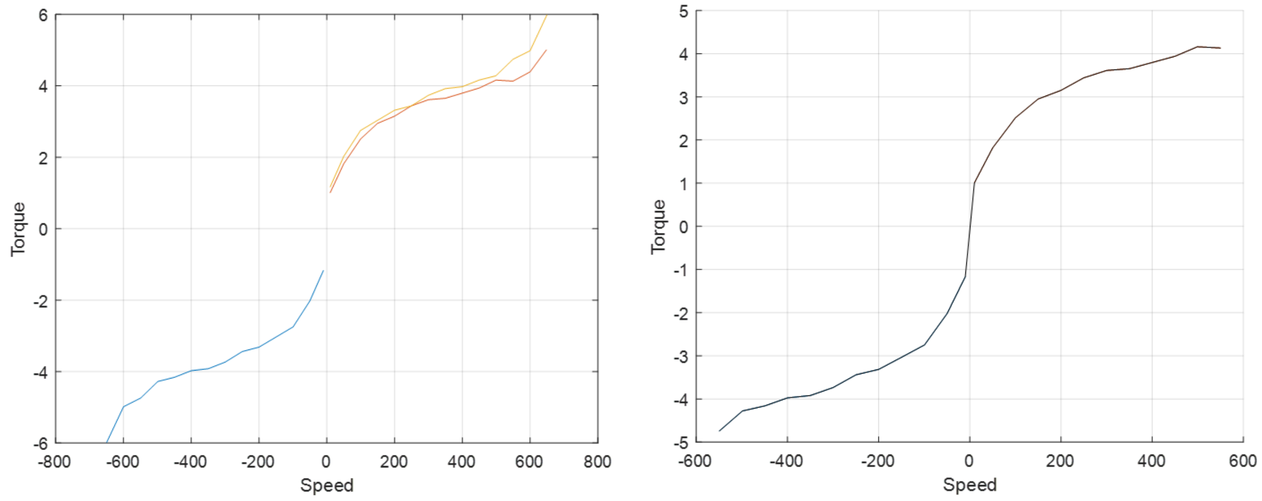


Figure 33 Key results from selected dynamic (left) and inertia (right) friction characterisation tests.

As a final illustrative example, selected results from the dynamic friction and inertia friction tests were compared. While the former test aims to assess the torque value that matches the dynamic mechanical frictions of the components inside the generator, the latter aims at experimentally estimating the effective inertia value of the rotating components. Results can be compared in a speed vs. torque profile; Figure 33 allows such comparison to be made, yielding similar results, which can in turn be used to e.g. assess the information supplied by the generator supplier(s) and/or calibrate numerical models that previously did not account for such losses.

6.3 Structural Components Rig Testing: CETO 6 WEC Belt System

Carnegie Clean Energy is the developer of a WEC named "CETO6" and was selected by the IMPACT consortium as the first company accessing the structural components test rig, for demonstrating the capabilities of this new infrastructure. The aim of the test was to evaluate the characteristics, tracking and long-term capabilities of a belt to be used in the CETO6 translation system. The test campaign had four main aims:

1. To characterize the belt in terms of load-deformation curve.
2. To check eventual variation of load during the belt rotation at slow speed, with a fixed carriage position.
3. To characterize the belt tracking capability for different combinations of load, speed, twist and fleet angles.
4. To ensure the belt can withstand the equivalent of three years of operation for the EuropeWave case study.

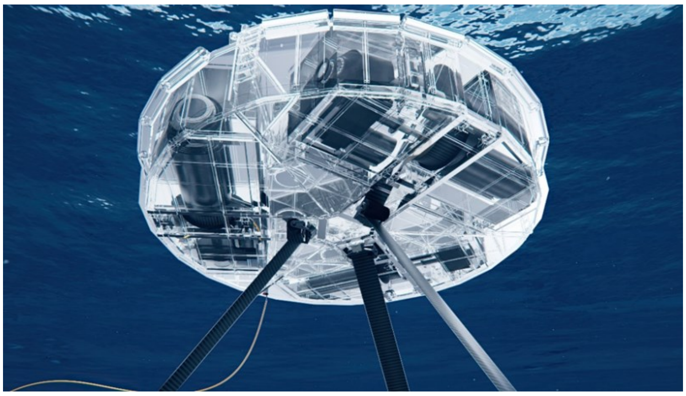


Figure 34 The CETO 6 WEC [17].

6.3.1 Test planning

The activities related to the planning and preparation of tests were in great part focused on the design, manufacturing and commissioning of the equipment required by the setup requested by CCE to be installed and operated. Indeed, while the structural components rig is designed for hosting large-scale components subject to multi-axial mechanical loads, each DUT and type of test require their own specific interfaces to realize the desired setup allowing to execute the experimental campaign. The methodology described in Section 4 was drafted for this case study and it proved to be useful for the introduction of topics such as: facilitating the understanding of loading conditions simulated by test, definition of acceleration factor, preliminary tests required before the effective campaign, type and number of transducers to be used. These aspects were useful to furtherly define the test plan document and to facilitate the planning and preparation of the experimental campaign.

The IMPACT testing methodology framework shown in Table 6 was applied to the CETO6 WEC belt system; the result of this work is provided in Table 15. The characterisation of the belt's endurance profile is at the core of the proposed test plan, with most of the input blocks being addressed via an experimental approach. Scaling was deemed to be not applicable due to the characteristics of the test and to the capability of the rig to target the full-scale device. Accelerated testing was enforced via a numerical approach, by considering the number of cycles the system would be subject to in the real application and the corresponding load at which it would be tensioned. In this application, the acceleration factor would be given by the rotational speed of the motor while loads would be kept aligned with the level experienced in normal and survival conditions.

Table 15 IMPACT methodology building blocks for the CETO6 WEC belt test campaign.

Foundation block	Functional block	Input block	Outline description
Pre-processing	Test conditions	Environmental conditions	Normal sea state (NSS) weighted by Occurrence.
		WEC status	Power production during normal and survival conditions. Belt unloaded during other states.
	Test set-up	Testing strategy	Accelerated testing (increased speed through belt rotation).
		Scaling assessment	No scaling.
		Target machine set-up	N/A
	Rig set-up	Hardware set-up	Geared motor for belt rotation. Mechanical tensioning system based on trapezoidal screw.
		Preliminary rig test	Sheave n.3 rotation, using geared motor. Sheave n.1 linear motion, using the trapezoidal screw.
Processing	DUT & transducers installation	DUT installation	Belt.
		DAQ system set-up	Rotary encoder (sheave n.3 rotation). Linear encoder (sheave n.1 linear motion). Load cell (applied tension from sheave n.1). Thermal gauge (on sheave n.3 support bearings).
	Basic testing	Signal tests	Belt run-in: signals from transducers to be checked.
		DUT model calibration	DUT model checks: expected strain vs. load.
		DUT characterisation	Strain vs. load (static and scanning test). Operating speed limit (for each specific configuration). Belt tracking.
	Advanced testing	DLC 1.1 test programme	Endurance characterization.
		Signal monitoring (DUT and rig)	Load, speed, absorbed current.
Post-processing	Inspection	DUT status	Visual inspection.
		Rig status	Visual inspection.
	Data quality	Data quality check	Bias.
		Raw data filtering	N/A
	Data analysis and reporting	Metrics assessment	Endurance metrics.
		Uncertainty assessment	Consider measurement, analysis and setup errors.
		Reporting	Characterization and reliability driven.

Theoretical	Numerical	Experimental

Figure 35 shows the damage modes that can occur when the belt is in service. While cyclic bend over sheave (CBOS) and tension are common damage modes which stress uniformly the fibres over the belt width, fleet and twist apply a non-uniform stress which affects the belt differently over its width. The test equipment to be mounted on the rig was designed to replicate the following conditions, therefore simulating the in-service loading:

- Cyclic Bend Over Sheave (CBOS): it causes sawing between cord fibres as they move relative to one another when passing the pulley. This relative motion comes from the bending and unbending of the belt.
- Tension: it increases the loading on the fibres, accelerating CBOS.
- Fleet: the cords on one side of the belt see increased tension while the others see load alleviation.
- Twist: the outer cords see load concentration while the centre cords see load alleviation.

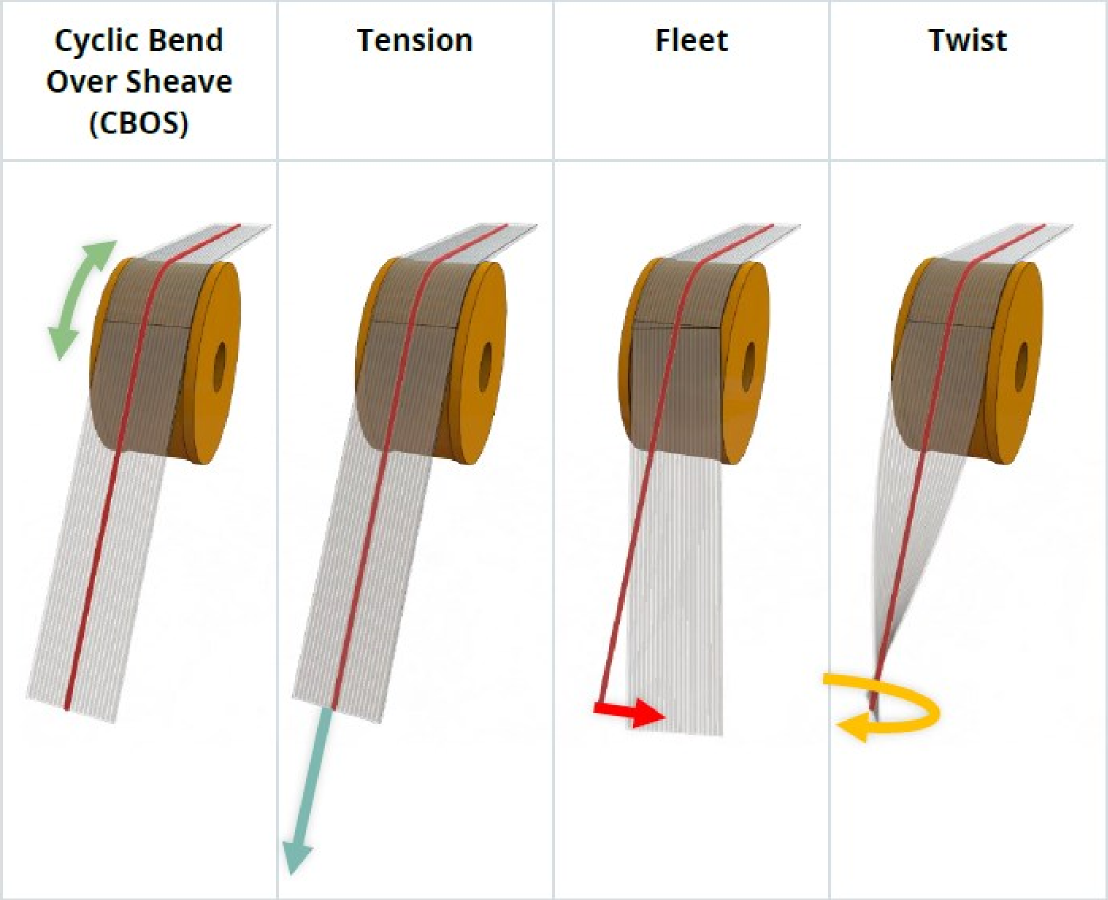


Figure 35 Damage mode definitions (left) and supporting descriptions (right).

A closed-loop belt arrangement was proposed for the experimental campaign, as it would allow to reach a higher acceleration factor during endurance tests (in comparison to using an open loop belt with reversing cycling). Figure 36 shows the final setup of the rig with the belt testing equipment installed. In particular, red arrows show the two actuation systems used for tensioning (trapezoidal screw) and running (geared motor) the belt, respectively. Green arrows illustrate the overall motions induced by such systems. The variables in the characterisation test programme included combinations of belt twist and fleet angles, tension load and motor speed: Figure 37 (left) shows the system of pushrods arrangement (with respective numbering) while Figure 37 (right) shows the consequent degrees of freedom of each sheave which allows application of twist and fleet angles on the belt.

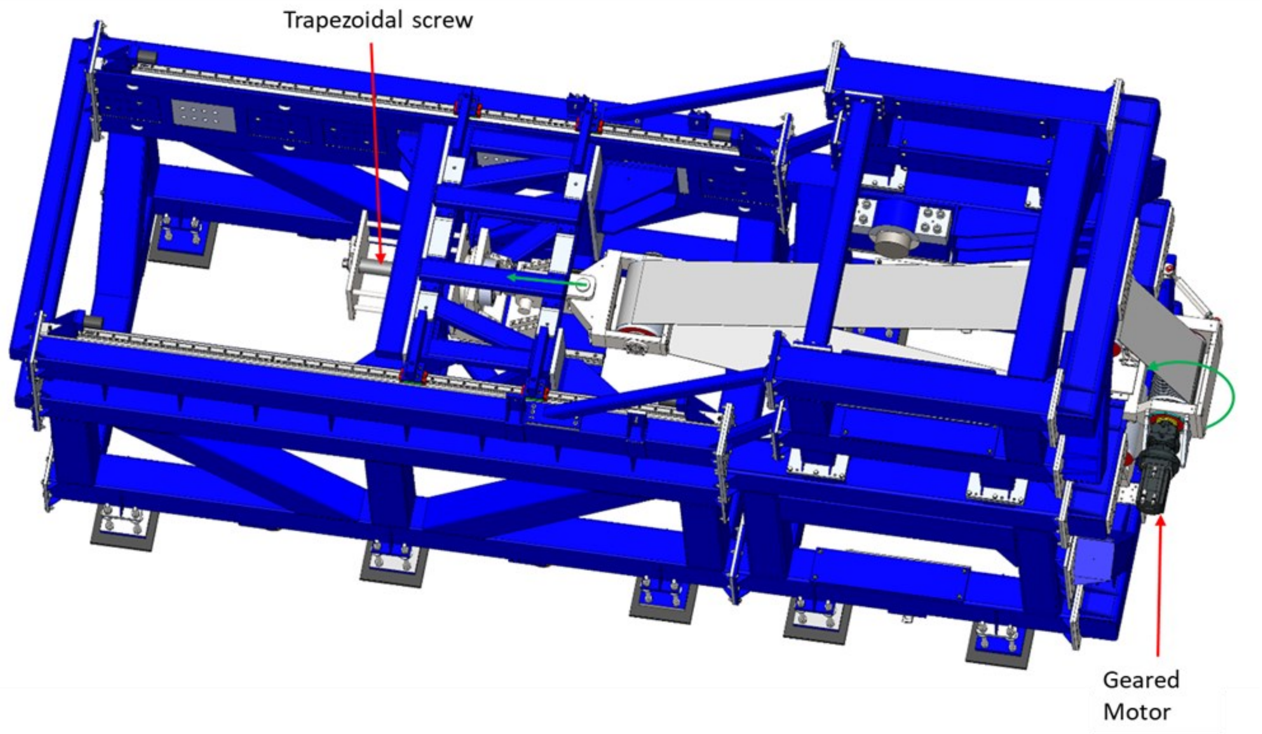


Figure 36 Final rig setup, with indication of actuation systems.

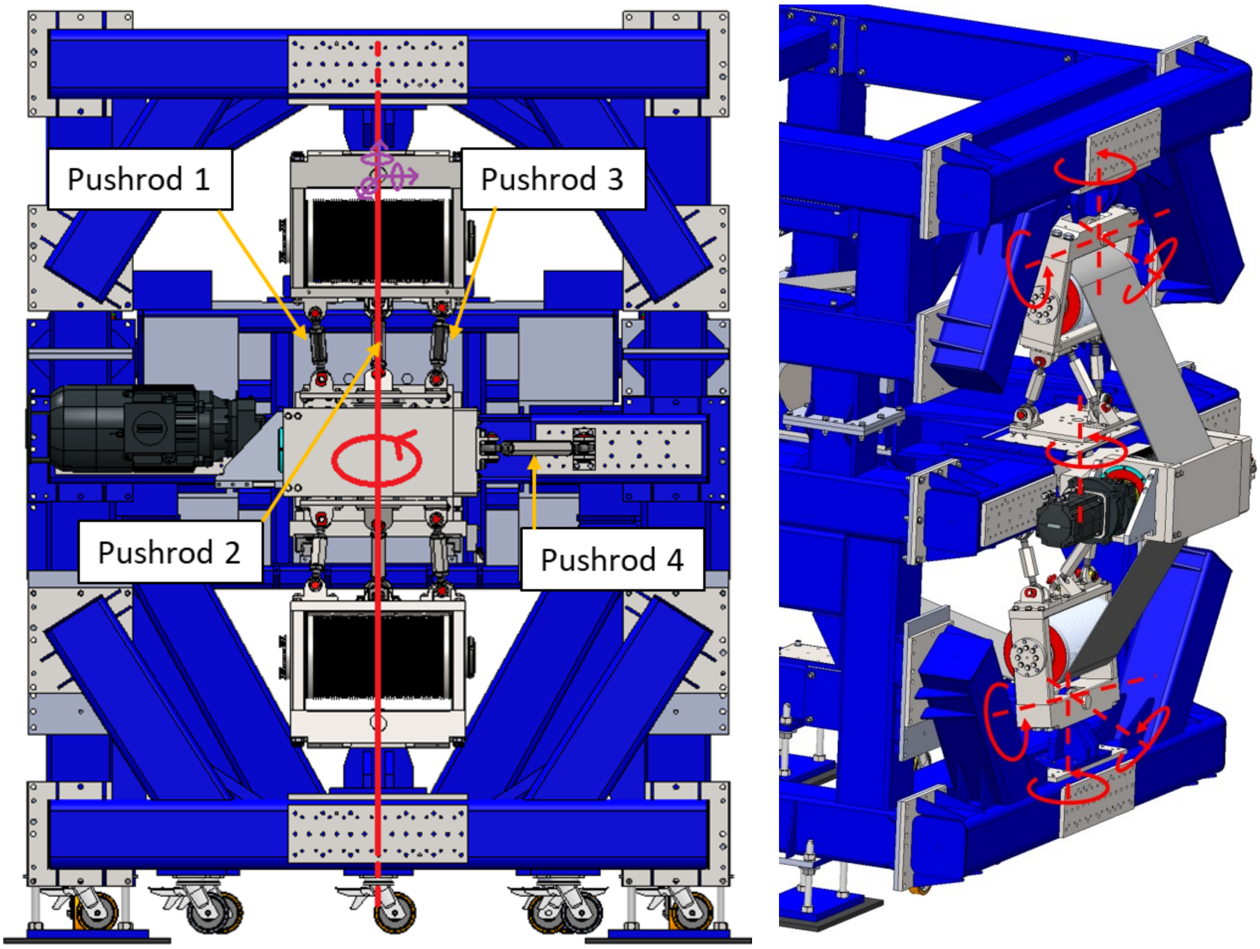
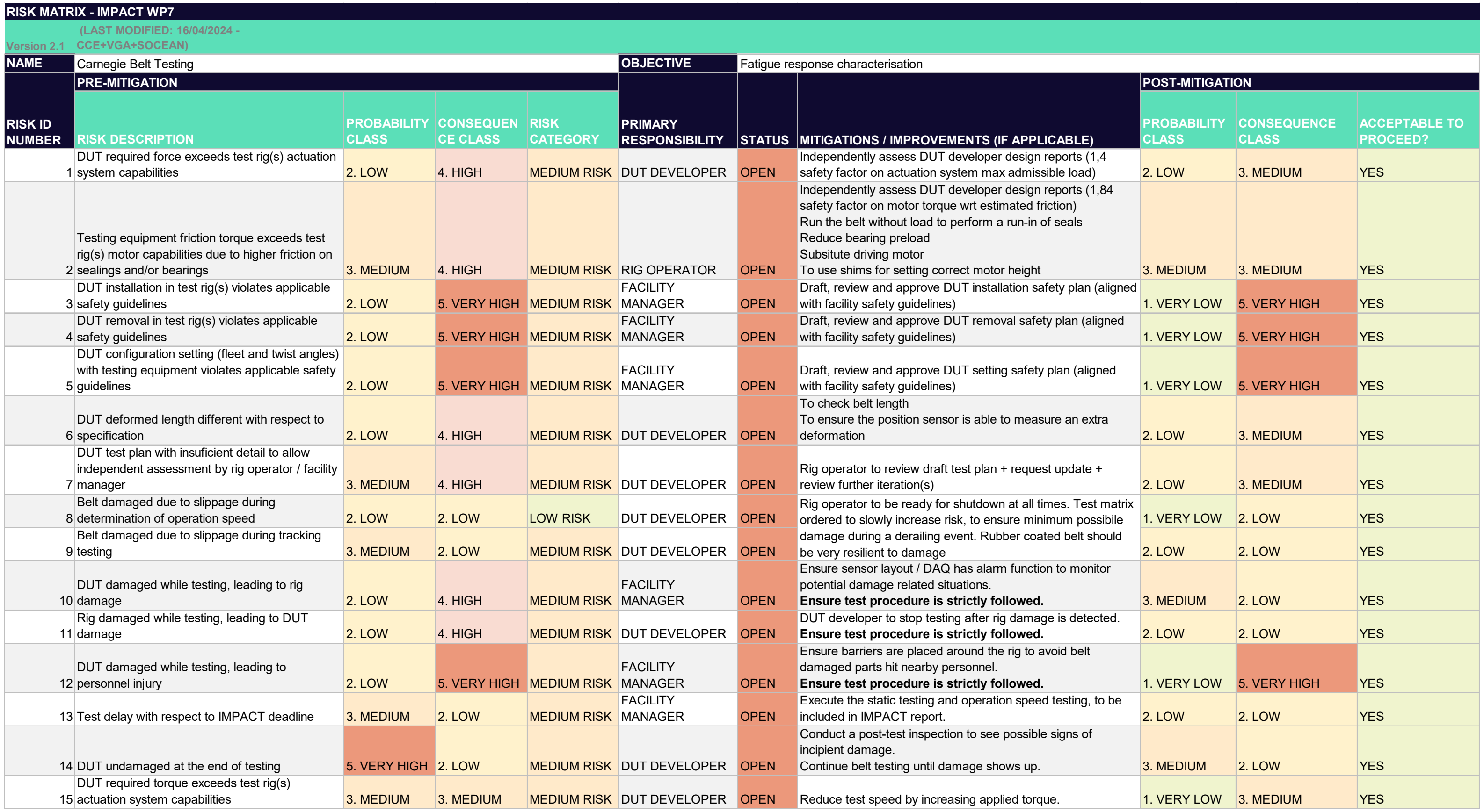


Figure 37 Sheaves numbering and setup inducing twist.

6.3.2 Risk assessment

Following the IMPACT risk assessment framework – see Section 6.1.2 – and using the risk matrix template illustrated in Appendix B, a risk matrix specific to the CETO6 WEC Belt System test plan was developed by CCE and the IMPACT consortium. The resulting matrix is illustrated in Figure 38. A total of fifteen risks were identified; eight of the identified risks were assigned to the DUT developer, six to the facility manager and one to the rig operator. At the risk pre-mitigation status, all but one of the identified risks were characterised as 'medium' risk, with the remaining one being identified as a 'low' risk. Following the methodology detailed in Section 6.1.2, at post-mitigation level all the risk were deemed as acceptable to proceed with the tests.



RISK MATRIX - IMPACT WP7

Version 2.1 (LAST MODIFIED: 16/04/2024 - CCE+VGA+SOCEAN)

NAME Carnegie Belt Testing

OBJECTIVE Fatigue response characterisation

	PRE-MITIGATION							POST-MITIGATION		
RISK ID NUMBER	RISK DESCRIPTION	PROBABILITY CLASS	CONSEQUENCE CLASS	RISK CATEGORY	PRIMARY RESPONSIBILITY	STATUS	MITIGATIONS / IMPROVEMENTS (IF APPLICABLE)	PROBABILITY CLASS	CONSEQUENCE CLASS	ACCEPTABLE TO PROCEED?
1	DUT required force exceeds test rig(s) actuation system capabilities	2. LOW	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	Independently assess DUT developer design reports (1,4 safety factor on actuation system max admissible load)	2. LOW	3. MEDIUM	YES
2	Testing equipment friction torque exceeds test rig(s) motor capabilities due to higher friction on sealings and/or bearings	3. MEDIUM	4. HIGH	MEDIUM RISK	RIG OPERATOR	OPEN	Independently assess DUT developer design reports (1,84 safety factor on motor torque wrt estimated friction) Run the belt without load to perform a run-in of seals Reduce bearing preload Subsitute driving motor To use shims for setting correct motor height	3. MEDIUM	3. MEDIUM	YES
3	DUT installation in test rig(s) violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT installation safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
4	DUT removal in test rig(s) violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT removal safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
5	DUT configuration setting (fleet and twist angles) with testing equipment violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT setting safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
6	DUT deformed length different with respect to specification	2. LOW	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	To check belt length To ensure the position sensor is able to measure an extra deformation	2. LOW	3. MEDIUM	YES
7	DUT test plan with insuficient detail to allow independent assessment by rig operator / facility manager	3. MEDIUM	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	Rig operator to review draft test plan + request update + review further iteration(s)	2. LOW	3. MEDIUM	YES
8	Belt damaged due to slippage during determination of operation speed	2. LOW	2. LOW	LOW RISK	DUT DEVELOPER	OPEN	Rig operator to be ready for shutdown at all times. Test matrix ordered to slowly increase risk, to ensure minimum possibile damage during a derailing event. Rubber coated belt should be very resilient to damage	1. VERY LOW	2. LOW	YES
9	Belt damaged due to slippage during tracking testing	3. MEDIUM	2. LOW	MEDIUM RISK	DUT DEVELOPER	OPEN		2. LOW	2. LOW	YES
10	DUT damaged while testing, leading to rig damage	2. LOW	4. HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Ensure sensor layout / DAQ has alarm function to monitor potential damage related situations. **Ensure test procedure is strictly followed.**	3. MEDIUM	2. LOW	YES
11	Rig damaged while testing, leading to DUT damage	2. LOW	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	DUT developer to stop testing after rig damage is detected. **Ensure test procedure is strictly followed.**	2. LOW	2. LOW	YES
12	DUT damaged while testing, leading to personnel injury	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Ensure barriers are placed around the rig to avoid belt damaged parts hit nearby personnel. **Ensure test procedure is strictly followed.**	1. VERY LOW	5. VERY HIGH	YES
13	Test delay with respect to IMPACT deadline	3. MEDIUM	2. LOW	MEDIUM RISK	FACILITY MANAGER	OPEN	Execute the static testing and operation speed testing, to be included in IMPACT report.	2. LOW	2. LOW	YES
14	DUT undamaged at the end of testing	5. VERY HIGH	2. LOW	MEDIUM RISK	DUT DEVELOPER	OPEN	Conduct a post-test inspection to see possible signs of incipient damage. Continue belt testing until damage shows up.	3. MEDIUM	2. LOW	YES
15	DUT required torque exceeds test rig(s) actuation system capabilities	3. MEDIUM	3. MEDIUM	MEDIUM RISK	DUT DEVELOPER	OPEN	Reduce test speed by increasing applied torque.	1. VERY LOW	3. MEDIUM	YES

Figure 38 Risk matrix - CETO WEC belt system test plan.

6.3.3 Test setup

The structural components test rig setup, including the component positioning, is detailed in Figure 36 and Figure 37. Together with the draft setup scheme in Figure 39, the 3D file defining test conditions and related loads, CCE also indicated the instrumentation to be used during the test for measuring the parameters of interest. These transducers are summarized in Table 16. It should be noted that the measurement of tension (through test cell), carriage position (through optical encoder), motor position and speed (through rotary encoder) are part of the IMPACT testing campaign scope of work (with the setup to designed and commissioned by VGA). On the contrary, the application and acquisition of strain gauges (used only during static tests) was a work conducted by CCE.

It is relevant to specify that the design, manufacturing and assembly of this equipment was conducted within the context of the ACHIEVE Phase 2 project, as part of the EuropeWave Horizon 2020 project (Grant Agreement 883751)[16].

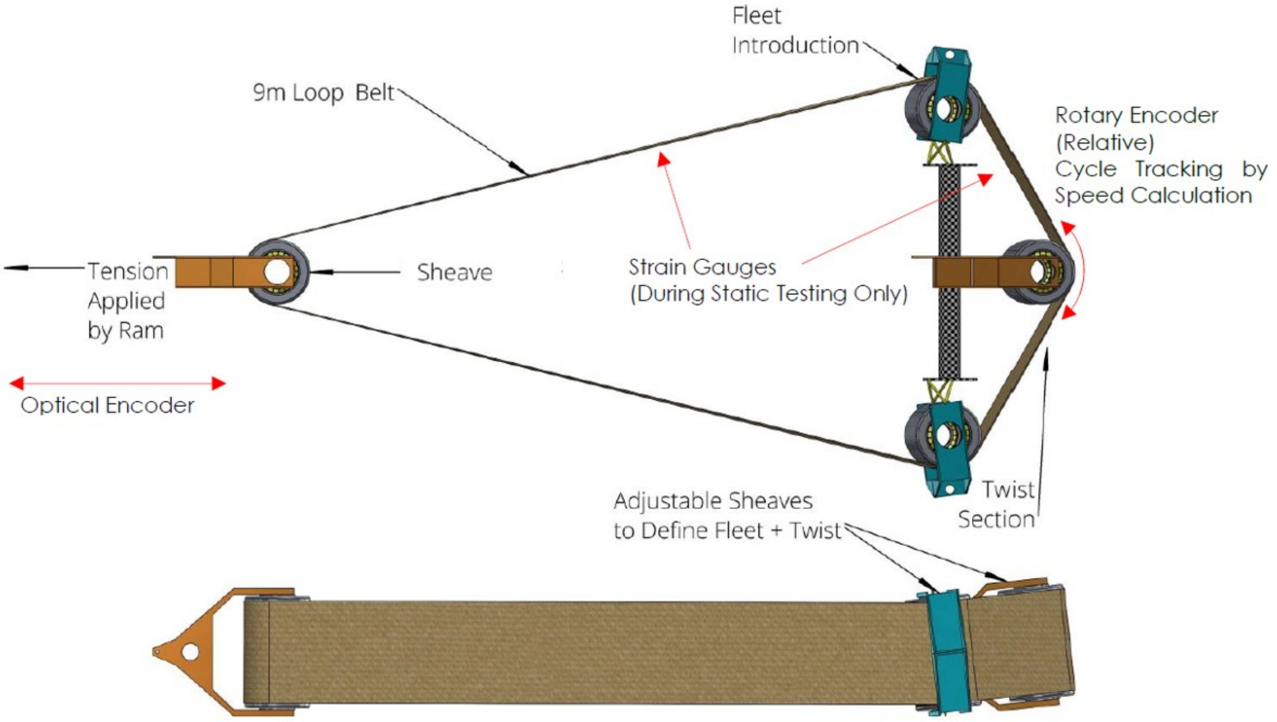


Figure 39 Test rig setup, including belt positioning [18].

Table 16 Overview of test rig sensors [18].

Sensor	Purpose
Load sensor on tension ram	Verify the load applied to the belt
Position sensor on tension ram	Monitor the elongation of the belt
Encoder on motor shaft	Monitor the belt position around the loop, for tracking number of cycles and belt speed.
Strain gauge array applied to belt	Monitor localised elongation due to twist and fleet

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[16] https://www.europewave.eu/

6.3.4 Test execution

An overview of the tests conducted on the structural component test rig, including a detailed description of the procedure for each test programme, is provided in the following subsections.

DUT Characterisation Tests

The belt characterisation tests were conducted between the 22nd of April – 17th of May 2024 at VGA's test facility. The test programme comprised of:

- Quasi-static tests.
- Operation speed determination tests.
- Tracking tests.

Parameters to be varied in the characterisation test programme included combinations of belt twist and fleet angles, tension load and motor speed. The verification for the correct setting of the sheaves' angular position is based on:

- for twist angle: the measurement of the relative positions between the sheaves n.2 and n.4 with respect to their pushrods support plates, through lengths L1, L2, L3 and L4 (shown on the left and centre of Figure 40).
- For fleet angle: the measurement of the relative positions between the sheave n.3 jaw and a fixed point on the support structure, through length L5 (shown on the right of Figure 40).

The pushrods, made up by a couple of rod-ends and a hexagonal threaded rod, are used to set the position of the sheaves on the right side of Figure 39.

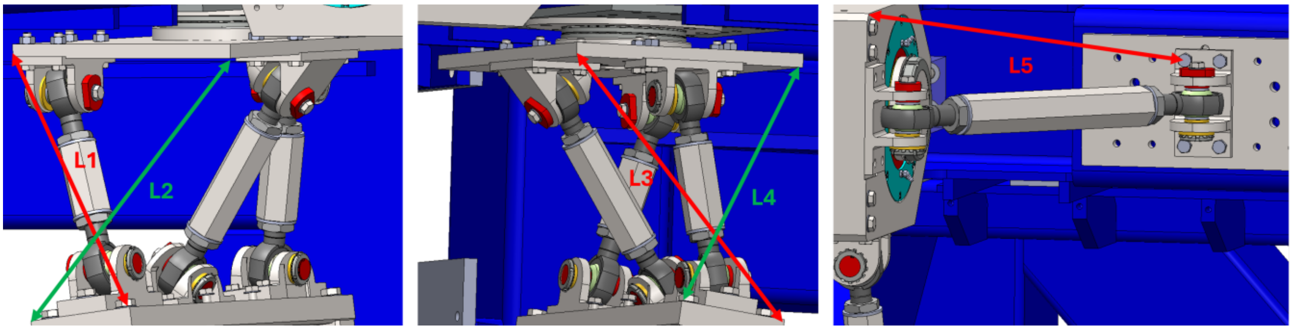


Figure 40 Belt test equipment. Lengths for inspection of correct twist (left and centre) and fleet (right) and settings.

Quasi-static Tests (QST)

The aim of quasi-static tests was to check the load variation during the belt rotation at slow speed and to verify eventual variations due to belt characteristics (e.g. different thickness at various lengths), incorrect setup or damage.

A step-by-step description of the test procedure for the quasi-static tests is provided below.

1. Set twist angle: Configure the three pushrods connecting sheaves n.2 and n.4 to their respective base plates (towards sheave n.3). Check the distances between pushrods and base plate according to Table 17 and Figure 40. Check that, due to backlash, the sheave assembly will not be positioned at a wrong angle once the belt is loaded.
2. Set fleet angle: Configure the pushrod connecting sheave n.3 to the rig structure. Check the distances between pushrods and base plate according to Table 17 and Figure 40.
3. Apply required tension: apply tension on the belt by displacing the carriage via the trapezoidal screw. Check that the correct value of tension is applied at the load cell; wait 1 minute for the value to stabilize within ±500N with respect to the target value,

4. Press “SAVE DATA” on the HMI of the rig control PC.
5. Select the speed target value and switch on the motor and release the brake by pressing the button “START TEST”.
6. After the speed reaches the target value and the belt has made at least one complete loop, press “STOP TEST” to stop the test.
7. Press “SAVE DATA” to stop data acquisition.
8. Rename the test file with the following template: “QST_(Test#)_(Twist)_(Fleet)_(Load cell reference tension)_(motor speed)”.
9. Write a comment about the test execution in the table of the related test log.

Table 17 Quasi-static tests: Fleet and twist configurations.

Setup #	L1 [mm]	L2 [mm]	L3 [mm]	L4 [mm]	L5 [mm]	Fleet p2p [mm]
1	393.36	478.23	481.36	405.74	533.13	460.20
2	393.36	478.23	481.36	405.74	556.43	484.72
3	393.36	478.23	481.36	405.74	562.24	490.83
4	393.36	478.23	481.36	405.74	568.04	496.93
5	393.36	478.23	481.36	405.74	573.82	503.03
6	393.36	478.23	481.36	405.74	579.60	509.11
7	393.36	478.23	481.36	405.74	602.62	533,37
8	381.37	479.86	481.20	418.66	505.31	430.99
9	381.37	479.86	481.20	418.66	528.76	455.65
10	381.37	479.86	481.20	418.66	534.60	461.79
11	381.37	479.86	481.20	418.66	540.44	467.93
12	381.37	479.86	481.20	418.66	546.26	474.06
13	381.37	479.86	481.20	418.66	552.08	480.19
14	381.37	479.86	481.20	418.66	575.28	504.611
15	370.04	482.03	482.036	431.88	476.36	434.46
16	370.04	482.03	482.036	431.88	499.95	459.45
17	370.04	482.03	482.036	431.88	505.83	465.69
18	370.04	482.03	482.036	431.88	511.70	471.93
19	370.04	482.03	482.036	431.88	517.56	478.16
20	370.04	482.03	482.036	431.88	523.42	484.39
21	370.04	482.03	482.036	431.88	546.78	509.25
22	359.30	484.89	482.67	445.44	447.84	441.11
23	359.30	484.89	482.67	445.44	471.53	466.10
24	359.30	484.89	482.67	445.44	477.44	472.35
25	359.30	484.89	482.67	445.44	483.34	478.61
26	359.30	484.89	482.67	445.44	489.24	484.87
27	359.30	484.89	482.67	445.44	495.13	491.13
28	359.30	484.89	482.67	445.44	516.16	518.63
29	349.31	488.34	484.33	459.211	419.15	450.54
30	349.31	488.34	484.33	459.211	442.92	475.18
31	349.31	488.34	484.33	459.211	448.86	481.37
32	349.31	488.34	484.33	459.211	454.79	487.57
33	349.31	488.34	484.33	459.211	460.71	493.77

Setup #	L1 [mm]	L2 [mm]	L3 [mm]	L4 [mm]	L5 [mm]	Fleet p2p [mm]
34	349.31	488.34	484.33	459.211	466.63	499.99
35	349.31	488.34	484.33	459.211	490.25	524.91
36	316.66	509.29	497.73	521.00	297.07	466.23
37	316.66	509.29	497.73	521.00	320.81	486.66
38	316.66	509.29	497.73	521.00	326.76	491.90
39	316.66	509.29	497.73	521.00	332.71	497.21
40	316.66	509.29	497.73	521.00	338.67	502.56
41	316.66	509.29	497.73	521.00	344.63	507.96
42	316.66	509.29	497.73	521.00	368.48	530.00

Operation Speed Determination (OSD) Tests

The aim of the operation speed determination test program was to determine the speed that can be kept stable for a prolonged period of time (e.g. 1 minute), to be used during the endurance tests.

A step-by-step description of the test procedure for the OSD tests is provided below.

1. Starting from the configuration set during each quasi-static test, press “SAVE DATA” on the HMI of the rig control PC.
2. Select ‘X’ speed and switch on the motor and release the brake by pressing the button “START TEST”.
3. After the motor speed reaches the target value and one minute of belt rotation at test speed is completed, press “STOP TEST” to stop the test.
4. Press “SAVE DATA” to stop data acquisition.
5. Rename the test file with the following template: “OSD_(Test#)_(Twist)_(Fleet)_(Load cell reference tension)_(motor speed)”.
6. Write a comment about the test execution in the table of the related test log.
7. Repeat the test by increasing the speed by ‘X’, until the maximum nominal value is reached, or any smaller value at which the test cannot be run, which could be due by one of the following issues:
    a. Belt Bowing: as the belt passes around the sheave path, it will tend to bow outwards. This will lead to extra belt tension, a tendency to lift off the sheaves, and a poor adhesion to the desired input variables.
    b. Motor Power: the motor has been specified for a maximum nominal speed. Assumptions around friction and the safety factors involved mean that it may be possible to reach faster speeds, up to the power capacity of the motor.
    c. Belt Tracking: at high fleet or twist the tracking ability of the belt may be speed dependent.
    d. Heat Buildup: temperature increases beyond the test equipment design limit (70°) will invalidate the test. To be measured with thermocouples installed within the motor.
    e. General Safety: fast moving parts present risk to safety. Excessive speeds will be avoided, informed by engineering judgement. Polycarbonate windows are available in shielding.

Tracking Tests (TT)

The aim of these tests was to see if the belt keeps the tracking ability, especially at small tension values. The speed of the belt was tested at the peak value the motor can reach. A step-by-step description of the test procedure for the tracking tests is provided below.

1. Starting from the configuration set during each quasi-static test, press “SAVE DATA” on the HMI of the rig control PC.
2. Select the peak speed and switch on the motor and release the brake by pressing the button “START TEST”.

After the motor speed reaches the target value and three rotations at test speed are completed, press "STOP TEST" to stop the test.

3. Press "SAVE DATA" to stop data acquisition.
4. Rename the test file with the following template: "TT_(Test#)_(Twist)_(Fleet)_(Load cell reference tension)_(motor speed)".
5. Write a comment about the test execution in the table of the related test log.

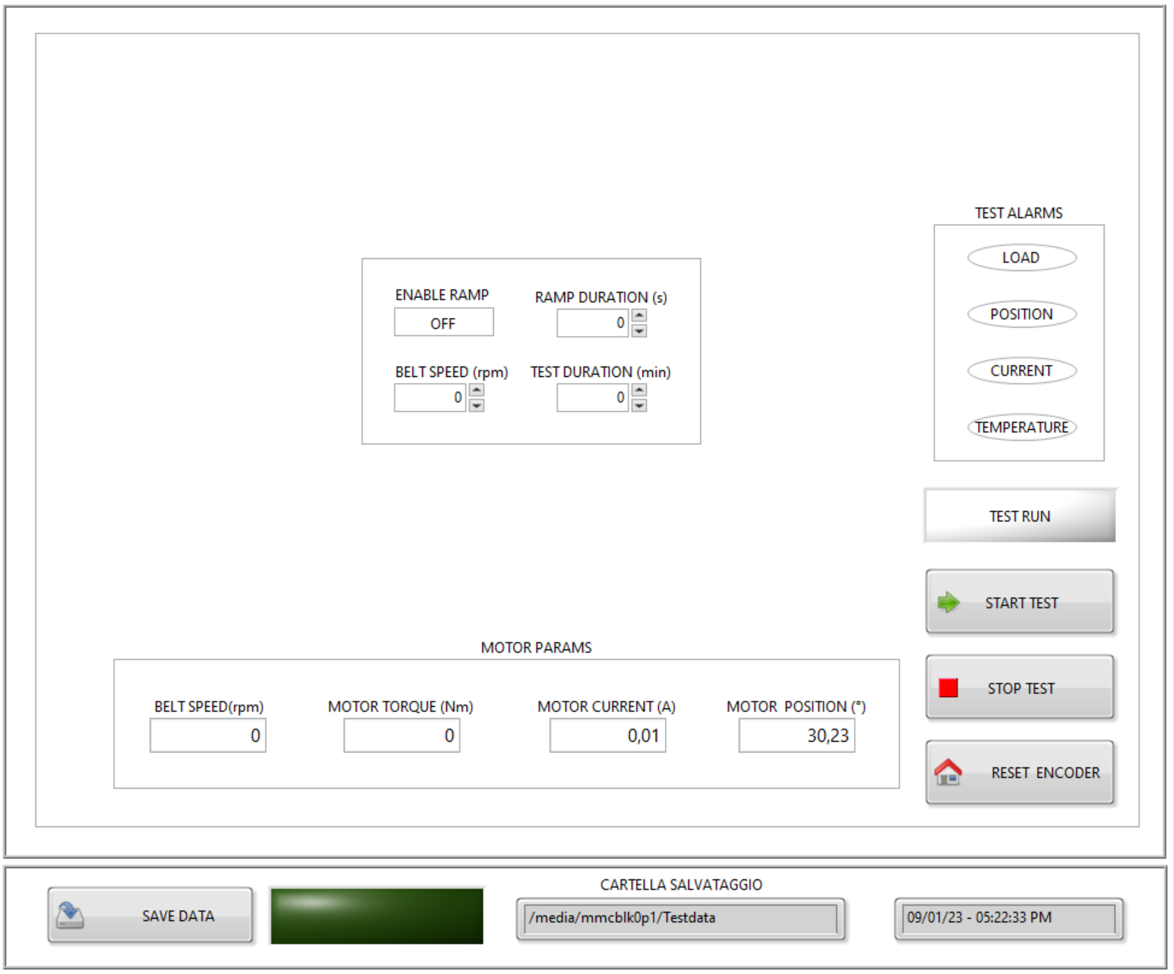
Endurance tests

The aim of endurance tests was to verify the capability of the belt to last for an equivalent duration of the deployment that Carnegie Clean Energy will carry out in 2025.

A step-by-step description of the test procedure for the endurance tests is provided below.

1. Set twist angle: Configure the three pushrods connecting sheaves n.2 and n.4 to their respective base plates towards sheave n.3. Check the distances between pushrods and base plate according to Table 17 and Figure 40. Check that, due to backlash, the sheave assembly will not be positioned at a wrong angle once the belt is loaded.
2. Set fleet angle: Configure the pushrod connecting sheave n.3 to the rig structure. Check the distances between pushrods and base plate according to Table 17 and Figure 40.
3. Apply required tension: Apply tension on belt by displacing the carriage via the trapezoidal screw connected to the carriage. Check the correct value of tension is applied at the load cell; wait the value to stabilize within ±500N for 1 minute.
4. Select on the HMI the speed value and test duration indicated in Test #1.
5. Press "SAVE DATA" on the HMI of the rig control PC.
6. Switch on the motor and release the brake by pressing the button "START TEST".
7. After test duration is reached, the motor will stop automatically. At this point press "SAVE DATA" to stop data acquisition.
8. Rename the test file with the following template: "ET_(Test#)_(Twist)_(Fleet)_(Load cell reference tension)_(motor speed)".
9. Write a comment about the test execution in the table of the related test log.

Figure 41 shows the HMI page used for endurance tests; ramp duration was kept at 30s, while belt speed and test duration were varied according to the test plan. Alarms were indicated by specific buttons eventually becoming red.



ENABLE RAMP OFF
RAMP DURATION (s) 0
BELT SPEED (rpm) 0
TEST DURATION (min) 0

BELT SPEED(rpm) 0
MOTOR TORQUE (Nm) 0
MOTOR CURRENT (A) 0,01
MOTOR POSITION (°) 30,23

CARTELLA SALVATAGGIO /media/mmcblk0p1/Testdata
09/01/23 - 05:22:33 PM

Figure 41 Rig HMI used for endurance tests.

6.3.5 Data post-processing and results

Following the generic principles of the IMPACT testing methodology framework, the post-processing stage activities included: inspecting the DUT(s) and the rig(s), checking data quality, analysing test data and reporting the results. A visual inspection of both the DUT and the rig(s) was also performed following the completion of the testing campaign, ensuring that no major changes / damages to the initial set-up occurred.

The initial step in the post-processing of the data is the assessment of the data quality, with the objective of checking and filtering the raw measured data, to remove errors, noise, outliers etc., in order to form a reliable basis for the subsequent data analysis activity. The raw data series for each of the analysed tests was also checked for data duplicates, outliers and data gaps.

Due to the absence of noise and bias, there was no need for filtering or additional quality checks on measured raw data. They were directly uploaded to a cloud folder shared with Carnegie Clean Energy in a way they could also review and postprocess them, especially when it was required to take a decision about when changing setup configuration (or if doing further tests following the measurement of eventual anomalies).

The most important outcome of the test is the definition of the operational limits of the belt, which could in turn inform the WEC design. The results of these tests remain confidential and therefore are not disclosed in this document.

6.4 Dual Hardware-In-the-Loop Testing

This section describes the Dual HIL testing campaign carried out simultaneously using the drivetrain, structural components, HIL control equipment and software. The campaign followed the previous test and aims at demonstrating the main objective of IMPACT, i.e. the feasibility of the Dual HIL technique as a beyond-state-of-the-art approach.

The architecture of the Dual HIL testing platform as used in the IMPACT demonstration campaign can be found in Section 5.4. The approach is to expand the HIL testing described in Section 6.2.4 by adding another interface towards the structural components rig as the WEC will be subject to the friction torque of the belt installed on the rig and under tension.

The test plan conducted for Dual HIL tests matches the one described in Table 14 and risk assessment is covered by the tables provided in Figure 29 and Figure 38.

6.4.1 Test execution

Figure 42 shows the speed profiles associated with test #9 of Table 14: the actuation input speed from the numerical model (dashed blue) is well followed by the structural components rig (red line) and the drivetrain rig (olive line) motor. While the former results in a more timewise but noisy response, the latter has a cleaner but delayed signal. However, the results of this test are acceptable, as both actuation systems can well follow the actuation profile, without any drop or discontinuity across the whole simulation.

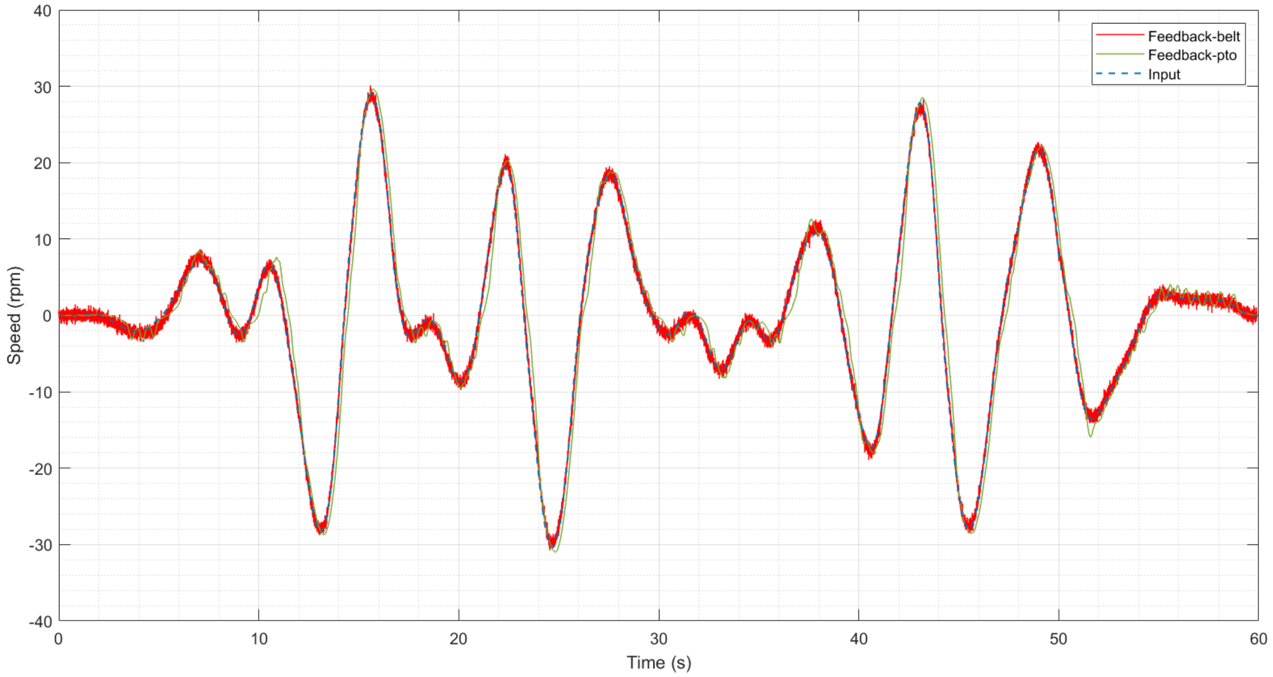


Figure 42 Input speed command from model (dashed blue), belt speed feedback (red) and generator speed feedback (olive) during a dual HIL test.

Figure 43 shows the feedback measured after the response of the DUTs to the actuation profiles presented in Figure 42. The belt torque (fuchsia line) is in line with the speed input shown in Figure 42 while the PTO measured torque (orange line) well follows the model expected value (green line). The overall torque given as feedback to the model (black line) confirms the dual HIL platform is correctly working, without causing instabilities to the model.

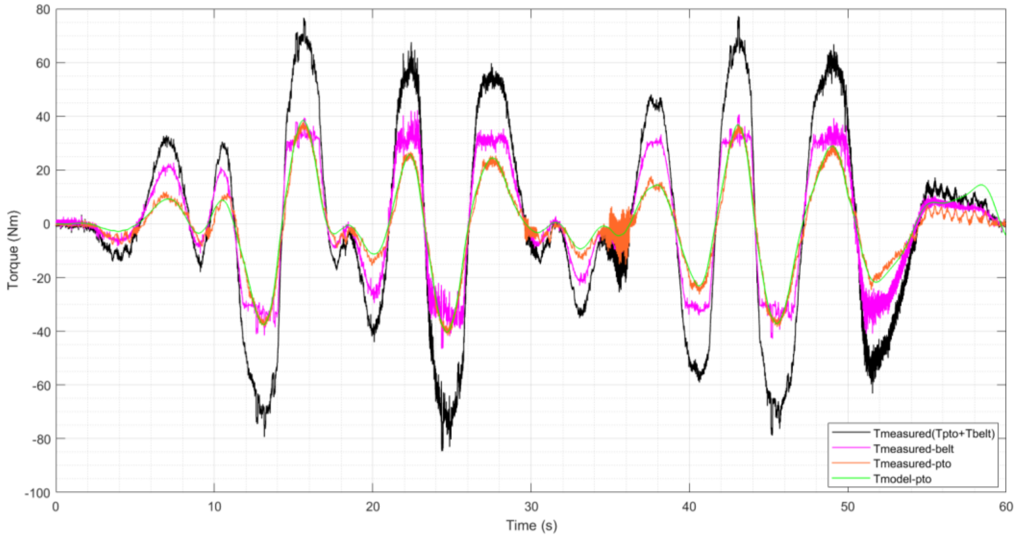


Figure 43 PTO model torque (green), real PTO torque measured on drivetrain rig (orange), belt torque measured on structural components rig (fuchsia) and overall torque fed back to the simulation model (black), during a dual HIL test.

6.4.2 Data post-processing and results

The torque profiles shown in Figure 44 are considered the main results of the Dual HIL tests, as they can reveal eventual interdependences between subsystems virtually connected to the same WEC. Considering the same input conditions of test#9, Figure 44 top shows the torque from the PTO tested on the drivetrain rig using the Dual HIL (orange line) and HIL (blue line) approaches. The PTO torque in Dual HIL test is sensibly lower with respect to HIL tests: the root mean square value is down to 48.9% while the peaks are down to 52% their initial values. The reason of this variation is due to the addition of the belt friction contribution on the overall device equilibrium condition. On the contrary, the effect of the real PTO with respect to its numerical models seems to not cause changes on the overall belt working conditions. This aspect means that, despite the increased disturbances when under full load, the belt performance (friction) is not affected by the presence of the real PTO, at least for the mentioned test. Considering this effect was observed also in the other tests, it can be deducted that, when an additional test campaign on the belt is required (e.g. simulating operation for different sea states from the ones in Table 14), the PTO numerical model could be used instead of conducting dual HIL tests (thus reducing the complexity of the experimental campaign).

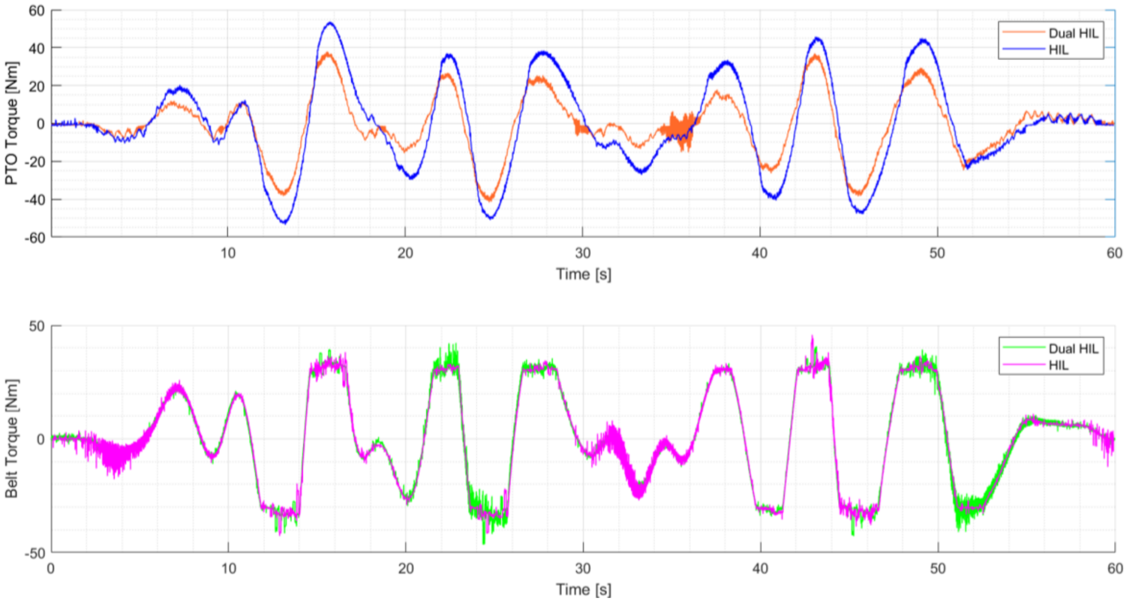


Figure 44 PTO (top) and belt (bottom) torque measured in dual HIL and HIL tests having the same input conditions.

The test campaign carried out using both drivetrain and structural components rigs simultaneously demonstrated that the IMPACT test platforms can be used together in a Dual HIL configuration to increase the level of fidelity of a test with respect to an at-sea deployment. In particular, two key subsystems of a device (in the IMPACT test case: a drivetrain and a mooring / mechanical power transmission component) were virtually connected to the same device model, feeding back their response to the input provided by the WEC-sea environment interaction (according to the simulated kinematics of the device). Before carrying out this type of tests, it is of importance to ensure the following aspects are addressed:

1. To have carefully and thoroughly characterized each DUT singularly, so that their numerical models can be created and integrated into the overall WEC model. The updated response of the WEC should be simulated using as input the sea states that are part of the test plan. An understanding of the differences between ideal and real subsystems should be achieved, so that their expected effect on the WEC behaviour is clear. This step should include HIL testing using one rig at a time, where the WEC model integrates the numerical block simulating the contribution of the device not under tests. Dual HIL should therefore be conceived as the last step of an experimental campaign where, after each system has been already tested and modelled, the eventual inter-dependences introducing a different response from each subsystem (or a different behaviour of the device) can be investigated.
2. The output kinematics and loads of the results from updated simulation should be checked against capabilities of both rigs. In particular, rig limits (loads, stroke, speed, acceleration, instantaneous and nominal power) should be higher than the simulation results, allowing to have a safety factor over possible test uncertainties (e.g. effects of interdependencies between subsystems). If possible, the capability of reaching these limits should be tested, using a non-HIL, open-loop setup. When “demand” profiles from numerical model exceed “supply” profiles from rig, a scaling approach should be considered.
3. Eventual risks associated to the combination of two test setups simultaneously used should be addressed, especially if the DUTs are active and/or managed by external systems (e.g. control logic).
4. Extreme cases of DUT damage and/or failure should be considered for safety of rig users and protection of test equipment (e.g. rigs, transducers, actuators, power electronics). Rigs must operate safely, independently from the entity of the response from DUTs.

7 Conclusions

The IMPACT project has successfully delivered a novel test platform and testing approach to support the acceleration of WEC development, thereby enhancing their performance, reliability, and survivability, through the usage of dry test rigs prior to deployment of prototypes at sea.

One of the most groundbreaking aspects of this project is the design and fabrication of the novel Dual HIL testing platform. This platform, along with the newly established test criteria and suggested metrics, represents a significant leap forward in the wave energy sector. By covering a large part of WEC sub-systems that affect the LCOE, the Dual HIL approach offers a comprehensive and integrated testing environment. The ability to conduct these tests using dry test rigs, alongside traditional tank testing, provides the opportunity to enhance the reliability and robustness of WEC systems.

The methodology employed in the IMPACT project, which involves a combination of theoretical, numerical, and experimental activities, has paved the way for a new paradigm in WEC development. By enabling concurrent testing of systems and providing all-round rigs for mechanical, structural, and PTO components, the project has set a new standard for how WECs should be developed and validated. This approach not only reduces testing time considerably but also ensures that WECs are better equipped to withstand the challenging marine environments they will encounter.

Furthermore, the availability of the new test rigs developed during this project opens up new avenues for post-project research and development. These rigs will be invaluable for ongoing efforts to refine WEC technologies, providing researchers and developers with the tools they need to continue pushing the boundaries of wave energy conversion.

The next steps to be carried out in follow up to the IMPACT project are:

1. To implement the recommendations included in this report for improving the quality of results and the overall outcome from experimental testing campaign.
2. Exploiting the IMPACT dual HIL testing platforms (named SWEET Lab[17]) for de-risking and advancing the development of ocean energy technologies.
3. Disseminating the IMPACT methodology framework as a tool for defining the details associated with the test campaign.
4. Calculating the devised metrics (applied to results of future test campaigns) to allow the comparison of test results to test object (especially associated to performance, reliability and survivability evaluation areas).
5. Establishing Dual HIL testing as a best practice to accelerate the pathway to market of the offshore energy sector.

In conclusion, the IMPACT project has laid the groundwork for a transformative shift in dry rig testing to support the development of WECs. The innovative Dual HIL testing platform, and the novel methodology introduced have the potential to significantly accelerate the deployment of wave energy technologies, making them more reliable, cost-effective, and ultimately, more viable as a key component of the renewable energy landscape. The continued use and development of the dry test rigs, in conjunction with existing tank testing approaches, will be crucial in ensuring the long-term success and sustainability of WEC technologies.

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[17] https://vga-srl.webflow.io/news-post/discover-sweet-lab

8 IMPACT publications and other sources

The project website[18] contains all public deliverables; these include scientific publications, but also blog posts, newsletters, press releases, a description of the project and work packages. Two technical workshops and a webinar were conducted by the project. One of workshops included a demonstration of the Dual HIL platform to the industry, technical and research communities. Information about these events are also included in the project website, and in the LinkedIn project page[19].

At the time of the submission of this report, the IMPACT project had released 12 publications, both conference papers and journal articles. Following the H2020 Open Access guidelines, published scientific publications, posters and selected presentations are available via the IMPACT community in Zenodo[20].

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[18] https://www.impact-h2020.eu/

[19] https://www.linkedin.com/company/impact-h2020/

[20] IMPACT Zenodo Community, Accessed on 15th August 2024. https://zenodo.org/communities/101007071/records?q=&l=list&p=1&s=10&sort=newest

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Appendix A – Review of metrics

The following selected evaluation criteria were addressed in the review [16]:

- *Power capture*. The process of converting energy from the natural resource by the interaction with a device, making it available as an input to a power take-off (PTO) sub-system (Hodges et al., 2021).
- *Power conversion*. Represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity (Hodges et al., 2021).
- *Reliability*. The probability that an item can perform a necessary function under given conditions for a given time interval (Hodges et al., 2021).
- Survivability. A measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event has passed (Hodges et al., 2021).
- Techno-economics. Denotes evaluation of indicators which are related to costs. Sometimes identified as performance indicators, these include the following evaluation areas: availability, affordability, and maintainability.
- Environmental impact. Focusing on the evaluation of the impact of WEC installations on the surrounding environment.

A.1 Performance metrics

A.1.1 Power capture

Table A.1 Power capture metrics in the wave energy sector

Name and Reference	Short Description
Power Capture (Hodges et al., 2021)	Matrix of average power capture in each sea state, in kilowatt (kW). Sea states are defined by combinations of significant wave height (H_s) and energy period (T_e), each split into bins (or intervals) along the matrix axes.
Capture Length (Hodges et al., 2021)	$L = P_C/A_P$, where L is the capture length in metres (m), P_C is the power capture, and A_P is the available power in kilowatt per meter (kW/m).
Capture Length Variability Matrix (Pitt, 2009)	Matrix with the standard deviation of the Capture Length in each sea state, in metres.
ACCW (Dallman et al., 2018)	Average climate capture width of a WEC at a specific location, in metres. Uses a set of weighted representative sea states in the scatter diagram to allow for testing WECs with a reduced number of environmental load conditions.
⟨ACCW⟩ (Dallman et al., 2018)	Average climate capture width of a WEC across representative locations of interest, in metres.
Capture Width Ratio (Babarit, 2015)	Nondimensional ratio between the capture length and a characteristic WEC dimension (both in metres). Also denoted as Hydrodynamic Efficiency. The diameter is used for circular devices while the characteristic dimension is based on the WECs maximum horizontal cross-sectional area for non-circular devices.
Duration Curves (Babarit et al., 2011)	Distribution of output power in function of fractions of the year.
Energy per Wave Force (Babarit et al., 2011)	Yearly energy output per unit characteristic excitation force, in kWh/kN.
Energy p/ Device Mass (Babarit et al., 2011)	Yearly energy output per characteristic mass, in MWh/ton.
Energy per Wet Surface (Babarit et al., 2011)	Yearly energy output per characteristic wetted surface area, in MWh/m^2.
q-factor (Folley and Whittaker, 2009)	Nondimensional ratio of the power output from a wave park to the sum of all the WEC if these were in isolation. Only applicable to wave parks.

Tank testing: continuous quantities (IEC, 2018)	For example, considering WEC dynamics and kinematics, identification of: Spectral response (spectral moments), Peak distribution (probability density function parameter values, mean, median, and 98th percentile), Onset of nonlinearity in regular waves.
Tank testing: discrete events (IEC, 2018)	For example, identification of: Local point loads, Green water occurrence, Slamming and Impact events.

Table A.2 Selected metrics from the wind energy sector.

Name and Reference	Short Description
Power curve (IEC, 2017)	Averaged power output as a function of wind speed. Equivalent to an element in the Power capture matrix.
AEP (IEC, 2017)	Annual Energy Production. It can be expressed for reference wind speed frequency distributions or be site specific. Equivalent to MAEP (Table 3) when taken before the PTO.
Power coefficient (IEC, 2017)	Equivalent to the Capture Width Ratio, the power coefficient C_p is given by: $C_P(V) = \frac{P(V)}{\frac{1}{2}\rho_0 A V^3}$, where V is the defined wind speed, P is the power output, ρ_0 is the reference air density, and A is the swept area of the wind turbine rotor.
Wind farm efficiency (IEC, 2017)	Equivalent to the q-factor, the wind farm efficiency, e, is given by: $e = \frac{1}{N}\sum_{i=1}^{N}\frac{P_i}{P_{0,i}}$, where N is the number of turbines in the farm P_i is the power output of the i^{th} turbine, and $P_{0,I}$ is the power of the i^{th} free-stream turbine.

A.1.2 Power conversion

Table A.3 Power conversion metrics in the wave energy sector.

Name and Reference	Short Description
Power Conversion Efficiency (Hodges et al., 2021)	Matrix (or surface-plot) of power conversion efficiency vs. PTO input power (input torque and angular speed or force and linear speed). Defined as the measure of the electrical power output (P) divided by the PTO power input (P_{PTO}): $\eta = P/P_{PTO}$
Power Performance (IEC, 2012)	Normalized power matrix. Calculated using the capture length and the average bin power. In this case, the capture length in Table 1 is calculated using the net electrical power (in kW).
MAEP (IEC, 2012)	Mean annual energy production, in Wh or kWh.
Capacity factor 1 (Dallman et al., 2019)	The capacity factor is the average electrical power divided by the rated power of the plant: $CF1 = P_{avg}/P_r$.
Capacity factor 2 (Ibarra-Berastegi et al., 2018)	Other references consider the definition of capacity factor as the average power divided by the peak power of the generator: $CF2 = P_{avg}/P_{r,peak}$ The difference from CF1 is the use of rated peak power, not rated power.
Peak to average power (Dallman et al., 2019)	Ratio between peak and average mechanical absorbed power: $PAP = P_{m,peak}/P_{m,avg}$ Values close to one are favourable.
PEI (Ibarra-Berastegi et al., 2018)	Based on the capture width definition. PEI is defined as the ratio between the average power generated over 5 min [kW] by the active turbines in Oscillating Water Column (OWC) systems and the wave energy flux [kW/m] at a specific sea location.

Table A.4 Metrics related to grid code requirements.

Name	Short Description
Active power gradient	Numerical value in MW/s or MW/min. Ramp rate of active power export during start-up and reconnection procedure of the power plant. Represents the active power increase during a specified period.

Controlled reduction of active power export	Value in MW/s. The generator must be able to reduce its active power following an external signal input. The rate of change for the output power should follow the grid code specifications.
Low Voltage Ride Through (LVRT)	Voltage profile representing voltage in p.u. and time in seconds. LVRT requirements specify minimum voltage amplitudes and time thresholds for which the generator must keep operation despite short-term low voltage conditions at PCC caused by grid faults.
Over Voltage Ride Through (OVRT)	Voltage profile representing voltage in p.u. and time in seconds. OVRT requirements specify maximum voltage amplitudes and time thresholds the generator must keep operation despite short-term over voltage conditions at PCC.
Controlled disconnection	Numerical value in seconds. Upon an external command signal, the plant must perform a controlled disconnection within a specified time.
Disconnection due to grid events	Unplanned disconnection caused by grid conditions outside the allowed frequency and voltage ranges, LVRT and OVRT thresholds, and trips due to protection systems.
Frequency range	Numerical range in % of nominal value (Hz) and time in seconds or minutes. Power plants should operate continuously within a specified frequency band. For frequencies outside the nominal band, the operation should last only for a specified time period.
Voltage range	Numerical range in % of nominal value (p.u). Power plants must operate continuously within a specified voltage range.
DC current injection	Numerical value in % kA. The amount of DC current injection in the grid is regulated by the grid code.
Flicker	Numerical value. As defined in (IEEE, 2015), "flicker is the subjective impression of fluctuating luminance caused by voltage fluctuations". The monitoring procedure is standardized and can be found in Section 5.2 of (IEEE, 2015).
Harmonics	Harmonic spectrum or numerical values. Harmonics are current and voltage signals with higher frequency components than the fundamental grid frequency. It can be characterized by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component (IEEE, 2019).

A.2 Reliability metrics

Table A.5 Reliability metrics used in the wave energy sector.

Name	Short Description
Mean Time to Failure (MTTF)	Numerical value expressed in hours. Reflects the component life expectancy.
Failure Rate	Probability of failure per unit time, in failures per hour, i.e. 1/MTTF.
MTBF	Mean time between failures. Reflects how long a component can operate without being repaired.
MFOP	Maintenance free operating periods. Reflects the component life expectancy, without maintenance.
ADP	Allowable degraded performance, non-dimensional.
MPPF	Maximum probability of premature failure.

Table A.6 Selected cross-industry reliability metrics with prospective relevance for WEC systems and components.

Name and Reference	Short Description
Failure Rate in cycles (Wood, 2001)	Probability of failure per cycle. Standard metric for reliability when usage is more relevant than time.
MCBF (Wood, 2001)	Mean Cycles Between Failures. Standard metric for reliability when usage is more relevant than time.
Failure Rate in distance (Wood, 2001)	Probability of Failure per Unit of Distance. Standard metric for reliability when distance is more relevant than time.

MMBF (Wood, 2001)	Mean Miles Between Failures. Standard metric for reliability when distance is more relevant than time.
Probability Of Failure on Demand (PFD) (IEC, 2010)	Numerical value expressed in percentage. Used in IT services and software.
Asset Health Index (Durán et al., 2020)	Dimensionless number representing the state of a system in terms of its deterioration. Allows for estimating the speed with which it deteriorates and project at what point is it close to the end of its life.
Reliability growth (Fries, 1996)	Measures the gradual product improvement through the elimination of design deficiencies. Applicable to repairable/upgradeable components.

A.3 Survivability metrics

Table A.7 Survivability metrics.

Name and Reference	Remark
Design conditions boundary (Hodges et al., 2021)	Beyond which a component, subsystem or device behaviour is unknown, and damage or loss of functionality may occur. Linked to Ultimate Limit State (ULS).
LEALD (Hodges et al., 2021)	Likelihood of Exceeding an Acceptable Level of Damage or loss of functionality, with or without taking suitable protective action. Numerical value. Calculated probability or likelihood estimate based on best available information.
Safety Survivability (Starling, 2009)	Probability that the converter will stay on station over the stated operational life. It seems exclusive for mooring systems, or station keeping systems in general.
Functional Survivability (Starling, 2009)	Probability that the converter will produce its rated energy (or an allowed degraded energy rating) without damage leading to the need for major unplanned removal or repair over the stated operational life. It does not provide a clear distinction between survivability and reliability.
Failure rate in survival mode per hour	Probability curve relating the chances of suffering a failure in a one-hour period of waves of a certain height outside the standard operating conditions.
Cumulative probability of 1-Year Survival	The survival distribution relative to the previous point, taking into account the wave climate on the deployment site.

A.4 Techno-economics metrics

Table A.8 Metrics for measuring WECs economic performance.

Name	Short Description
LCOE (Hodges et al., 2021)	The Levelized Cost of Energy is the ratio between lifetime costs and the energy production (e.g., in €/MWh). Its calculations require extensive information, probabilistic analyses, and sensitivity studies, especially for low Technological Readiness Levels (TRLs).
CAPEX (Hodges et al., 2021)	The Capital Expenditure (e.g., in €, €/MW, €/MWh) is an indicator of the cost at both early and late-stage development phases.
OPEX (Hodges et al., 2021)	OPEX (fixed and variable O&M costs) and energy generation (taking into account lifetime O&M activities and device downtime affecting availability) feed directly into LCOE.
Average climate capture width and Characteristic capital Expenditure (ACE) (Sergiienko et al., 2018)	A proxy to LCOE for evaluating and comparing WEC devices with different working principles where information is insufficient to calculate LCOE. It is specific to a particular site and its energy climate.

A.5 References to metrics definitions

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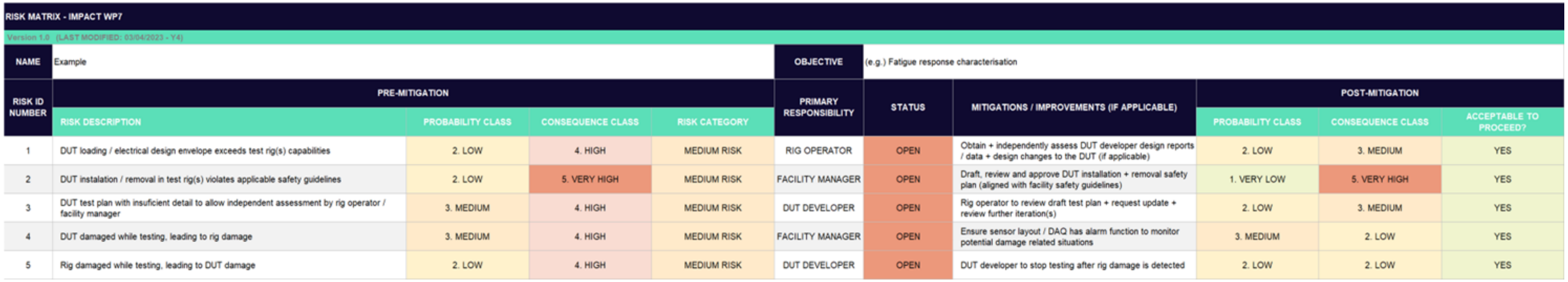
Appendix B - IMPACT Risk Matrix Template



RISK MATRIX - IMPACT WP7

Version 1.0 (LAST MODIFIED: 03/04/2023 - Y4)

NAME Example

OBJECTIVE (e.g.) Fatigue response characterisation

RISK ID NUMBER	PRE-MITIGATION				PRIMARY RESPONSIBILITY	STATUS	MITIGATIONS / IMPROVEMENTS (IF APPLICABLE)	POST-MITIGATION		
	RISK DESCRIPTION	PROBABILITY CLASS	CONSEQUENCE CLASS	RISK CATEGORY				PROBABILITY CLASS	CONSEQUENCE CLASS	ACCEPTABLE TO PROCEED?
1	DUT loading / electrical design envelope exceeds test rig(s) capabilities	2. LOW	4. HIGH	MEDIUM RISK	RIG OPERATOR	OPEN	Obtain + independently assess DUT developer design reports / data + design changes to the DUT (if applicable)	2. LOW	3. MEDIUM	YES
2	DUT instalation / removal in test rig(s) violates applicable safety guidelines	2. LOW	5. VERY HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Draft, review and approve DUT installation + removal safety plan (aligned with facility safety guidelines)	1. VERY LOW	5. VERY HIGH	YES
3	DUT test plan with insuficient detail to allow independent assessment by rig operator / facility manager	3. MEDIUM	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	Rig operator to review draft test plan + request update + review further iteration(s)	2. LOW	3. MEDIUM	YES
4	DUT damaged while testing, leading to rig damage	3. MEDIUM	4. HIGH	MEDIUM RISK	FACILITY MANAGER	OPEN	Ensure sensor layout / DAQ has alarm function to monitor potential damage related situations	3. MEDIUM	2. LOW	YES
5	Rig damaged while testing, leading to DUT damage	2. LOW	4. HIGH	MEDIUM RISK	DUT DEVELOPER	OPEN	DUT developer to stop testing after rig damage is detected	2. LOW	2. LOW	YES