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Verification through Accelerated testing Leading to Improved wave energy Designs

Deliverable 6.3

Metrics and targets for stage-gate assessment of ocean energy technologies

Version 1.0

2023-04-24

Lead participant: TEC

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Short	Type	
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PP	Restricted to other programme participants (including the Commission Services)	
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Executive Summary

This deliverable details the VALID project's work done in T6.2 "Targets for stage-gate assessment of wave energy technologies" (until February 2023). The activity aims to create an objective assessment of how well a technology performs against key criteria. The work has focused on the three critical components of the three User Cases proposed by the three wave energy technology developers, CorPower, IDOM and WavePiston. In this activity, we have:

- Identified the **main Evaluation Areas** affected by the critical component for each User Case
- Identified a set of **appropriate metrics** to be monitored during the hybrid testing
- Identified a set of design parameters that impact the LCOE
- Identified space of **physically measured variables** during the hybrid test campaign
- Determined some targets for the metrics
- Carried out a **stage-gate assessment** of the critical component technologies using the DTOceanPlus toolset

T6.2 is ongoing, and upon finalisation, the whole outcome of the activity will be documented in another deliverable, D6.5, "Progress on key metrics for stage-gate assessment of ocean energy technologies", in which following a reversed cost engineering approach, targets for the priority evaluation areas which critical components must achieve will be checked upon the finalisation of the hybrid testing campaign. Progress on costs will be exemplified with the help of the three technologies of the User Cases.

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Project partner names

- RISE Research Institutes of Sweden AB
- Fundacion Tecnalia Research and Innovation
- CorPower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
- Aalborg University
- AVL List GMBH
- WavePiston AS
- Delft University of Technology
- Aquatera Sustainability Ireland L.T.D.
- Julia F. Chozas, Consulting Engineer
- Yavin Four Consultants, Unipessoal LDA
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- Technical University of Denmark

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1 Introduction

1.1 Background

D6.3 "Metrics and targets for stage-gate assessment of ocean energy technologies" is the first public deliverable that collects the outcome of T6.2 of the VALID project. The end goal of T6.2 is to objectively assess how well the technology performs against **key criteria** using data generated by physical testing. In order to achieve this aim, during the activities in T6.2, some intermediate results should be achieved:

1. The definition of a set of **minimum requirements** and quality of the physical testing activities to test/demonstrate eliability and durability through accelerated lifetime testing.
2. Implementing a **reversed cost engineering** approach to establish targets/thresholds must be achieved by critical components in terms of reliability.

All the actors involved in the deployment of wave energy technologies will benefit from a stage-gate assessment:

- Technology developers deliver the expected engineering activities and present results clearly to potential customers and investors
- Public funders make efficient and open decisions, maximise the value of public support and avoid replication of funding
- Private investors build confidence in ocean energy with visibility of technology pedigree

The final aim is, therefore, to make wave energy technologies more transferrable and globally understood.

The activities in this task have made use of the H2020 DTOceanPlus software, with a particular focus on the Stage-Gate Design Tools, assisting the wave energy developers in the compilation of the activity checklist and thus checking their stage of development against a set of standardised activities that should be completed at each stage for any evaluation area.

In this deliverable, the initial activities within T6.2 are documented. In particular, the main outcome that has been documented involves:

- Identifying the **main Evaluation Areas** affected by the critical component for each User Case;
- Identifying a set of **appropriate metrics** to be monitored during the hybrid testing;
- The identification of a set of design parameters that impact the LCOE;
- The identification of space of **physically measured variables** during the hybrid test campaign;
- The determination of some targets for the metrics;
- A **stage-gate assessment** of the technology using the DTOceanPlus toolset;

T6.2 is ongoing, and upon finalisation, the whole outcome of the activity will be documented in D6.5, "Progress on key metrics for stage-gate assessment of ocean energy technologies", in which following a reversed cost engineering approach, targets for the priority evaluation areas which critical components must achieve will be checked. Progress on costs will be exemplified with the help of the three technologies of the User Cases

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1.2 Structure of the Report

This deliverable is organised into seven main sections and three annexes:

Section 1: Introduction, where the scope and structure of the deliverable are presented.

Section 2: The stage-gate development process, which introduces the main principles of a technology development process, the stages of wave energy development, the concepts of evaluation areas and metrics, stage activities, and the description of the methods and tools generally used for the evaluation.

Section 3: Approach and Methodology, which describes the aim and primary expected outcomes of the activities that we have carried out in T6.2. In particular, the organisation of the sessions for the workshop is detailed, and the materials used in those sessions and the methods adopted are described.

Section 4-6: Stage-gate assessment for UC1-3, in which each section provides an overview of each user case in VALID and the main outcomes of the activities in T6.2 at the time of writing and as an outcome of the workshops, in terms of key metrics, design parameters, physical variables, targets and stage-gate assessment .

Section 7, in which some concluding remarks and future work are wrapped up.

Nomenclature and references complete the deliverable. In the Annex, the standard reports of the stage-gate assessment (Activity Checklist) generated by DTOceanPlus are invclduded for UC#2 and UC#3.

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2 The Stage-Gate Development process

Technology performance assessment is a continuous process that needs to occur at every development level [1]. All stakeholders in wave energy can gain significantly from a broadly accepted evaluation system, including improved clarity, consistency, and development direction [2]. In order to reduce development risks, costs, and times, early design decisions based on objective criteria are essential.

The Technological Readiness Levels (TRLs), initially developed at NASA [3], have historically played a significant role in evaluating wave energy technologies. Several TRL definitions for wave energy have been put forth [4] [5]. In wave energy, it is common to group systematic TRL development into stages. Before moving on to the next development stage, a device or subsystem must satisfy the stage-gate requirements. The most common framework consists of five stages. It was first proposed at HMRC to reduce the financial and technological risks involved in developing wave energy devices [6]. Afterwards, it was adopted as best practice by IEA- OES [7] and FP7 EQUIMAR [8]. Eventually, it was recommended by IEC [9].

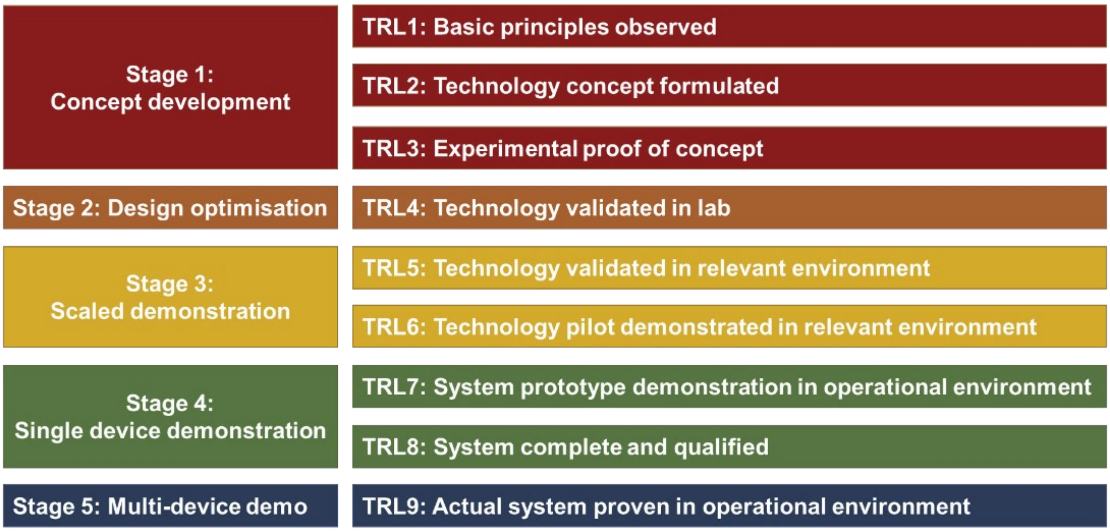

Figure 2.1: Technology Readiness Levels and IEC Stages

Wave energy technology development has been heavily influenced by evaluation approaches built on the LCOE. LCOE combines lifetime costs and energy production, two relevant stakeholder criteria, into a single metric. Since 2016, WES has fostered the development of performance metrics and tools for ocean energy technologies through workshops with extensive international cross-sector input [10]. Similarly, [11] have contributed to gaining a worldwide consensus by compiling a collection of existing Ocean Energy performance metrics for the farm level, the wave energy device, and its core subsystems (e.g. structure, PTO, control, mooring).

Performance assessment is inherently grounded in this concept of staged development. Based on this idea, IEA-OES is promoting the adoption of an international evaluation and guidance framework for ocean energy technologies [2]. Stages are loosely related to the TRL scale; the relevant metrics are evaluated at each stage gate.

Dividing the technology development process into stages gives all stakeholders clarity on expectations. Awareness of the stage activities and evaluation criteria throughout the development process enables public and private investors and technology developers to make informed decisions. A clear set of expectations makes it possible to monitor progress and success, which builds confidence in the technology.

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Nine evaluation areas are integrated into this framework, as depicted in Figure 2.2. Affordability is at the highest level of the evaluation hierarchy.

Figure 2.2: Evaluation Areas included in the Evaluation and Guidance Framework [2]

The definition of each evaluation area, along with their associated evaluation criteria (metrics), are provided in the following table.

Table 2.1: Definitions of evaluation areas and corresponding metrics (adapted from [2])

Evaluation Area	Definition	Evaluation Criteria
Power Capture	Power Capture is the process of extracting energy from the natural resource by interacting with a device and making it available as an input to a power take-off (PTO).	Power capture [kW] Capture length [m]
Power Conversion	Power Conversion represents the second step in the chain, whereby the mechanical power captured by the device is converted to electricity.	Power Conversion Efficiency [-]
Controllability	Controllability is the ability to implement control systems in a subsystem or device. It incorporates an evaluation of the benefits control can deliver and the reliance of a subsystem or device on it.	Category [0-4]
Reliability	Reliability is the "probability that an item can perform a necessary function under given conditions for a given interval".	Mean Time to Failure (MTTF) [h]

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Evaluation Area	Definition	Evaluation Criteria
		Failure Rate [-] Availability [%]
Survivability	Survivability is 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.	Design Conditions Boundary [-] Likelihood of exceeding an acceptable level of damage [-]
Maintainability	Maintainability is the "ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance".	Range of acceptable environmental conditions [m or s or m/s] Mean Time to Repair (MTTR) [h] Availability [%] Cost to Repair [€]
Installability	Installability is the ease with which a component, subsystem or device can be prepared, deployed at the operational open-water site and commissioned, resulting in operational readiness. Installability also includes the ease with which the component, subsystem or device can be recovered.	Range of acceptable environmental conditions [m or s or m/s] Mean Time to Install (MTTI) [h] Transit speed [knots] Cost to Install [€]
Manufacturability	Manufacturability is defined as the ability for the technology to be manufactured quickly, cheaply and with minimum waste, and therefore its compatibility with the supply chain's capability, readiness and maturity.	Manufacturing Readiness Level (MRL) [-] Time to manufacture [h] Cost to manufacture [€]
Affordability	Evaluation of Affordability relates to the cost of electricity generated from the wave resource.	Capital Expenditure (CAPEX) [€] Operational Expenditure (OPEX) [€] Levelised Cost of Energy (LCOE) [€]

The first-of-kind implementation of this framework has been produced in the EU H2020-funded DTOceanPlus suite of design tools for ocean energy systems [12]. Assessments are grouped into four main categories, namely SPEY (System Performance and Energy Yield), RAMS (Reliability, Availability, Maintainability and Survivability), SLC (System Lifetime Costs), and ESA (Environmental and Social Acceptance). These assessments feed into the DTOceanPlus Stage-Gate tool for the overall assessment of ocean energy technologies.

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Wave energy technologies require assessment criteria that can be applied at various system aggregation levels. To assess the subsystem's impact on global performance, it must be set in the context of a device and, in turn, placed in the context of a wave farm [2]. Figure 2.3 illustrates several frames of reference of technologies, including the external environment to consider the installation of the wave farm in a specific deployment site and the commercial aspects of the wave energy project.

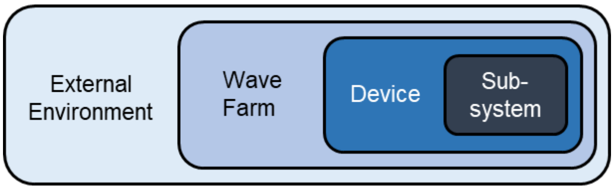

Figure 2.3: Various system boundaries for a wave energy assessment

VALID focuses its research activities on assessing the impact on global performance at the subsystem level. The project aims to de-risk the whole WEC design process by developing an integrated and open platform for testing critical components and subsystems.

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3 Approach and Methodology

The stage-gate assessment of ocean energy in VALID involved the developers of the technologies in the User Cases, i.e. CorPower, IDOM and WavePiston. A mixed approach was used to achieve the task's objectives: two bilateral workshops and a set of offline activities were designed and carried out to perform the described activities.

3.1 Aim and Outcomes

The general purpose of a stage-gate assessment for ocean energy technologies is to evaluate how well a technology performs against objective key criteria. This concept has been adapted for the VALID project by establishing the evaluation criteria based on analysing the hybrid testing campaign outcomes for the three user cases.

For each technology, two main activities were carried out before the realisation of the hybrid test campaign:

1. An analysis of the primary metrics, design parameters and physical variables and targets (in terms of the main metrics) that are the object of the hybrid testing of the critical component analysed in each user case
2. An initial stage-gate assessment of the evaluation areas most affecting the Levelized Cost of Energy (LCOE).

These two stages are documented in this document, D6.3. After fulfilling the test campaigns, the targets defined in this document will be checked against the outcome of the hybrid testing. The stage-gate assessment will eventually be updated based on the knowledge acquired empirically.

3.1.1 Aim and Methodology

The core of the activities in T6.2 focuses only on the **critical subsystems**, different for each user case, and their impacts on the final LCOE. This constitutes one of the significant differences with T6.3, which on the contrary, focuses the attention on a holistic techno-economic model of the device, estimating the LCOE.

A reverse engineering approach to the equation of LCOE has been adopted in T6.2. For this purpose, a simplified formulation for LCOE is represented in (1).

$$LCOE = \frac{Lifetime\ Cost\ (LC)}{Yield} \quad (1)$$

LC represents the Lifetime cost and accounts for the capital expenditure *CAPEX* and operational costs *OPEX*, i.e. as in (2).

$$LC = CAPEX * FCR + OPEX\ . \quad (2)$$

FCR represents the Fixed Charge Rate, which is supposed to be constant throughout the project's life *n* and depends on the discount rate *d*, as in (3).

$$FCR = \frac{d}{[1-(1+d)^{-n}]} \quad (3)$$

In the simplified approach of T6.2, *CAPEX* in (4) depends on two major components: the raw cost of the components, as a multiplier of the unit cost, the quantity (mass) of the subsystem and a safety factor, and the cost for installation, mainly formed by the cost of the labour and the Mean Time To Install *MTTI*.

$$CAPEX = Unit * Mass * S_F + Labour * MTTI \quad (4)$$

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Similarly, the *OPEX* in (5) is estimated by summing up two contributions: the cost of the spares, accounting by the number of times that in a year (*8766* hours) they should be replaced based on their Mean Time To Failure (*MTTF*) and the cost of the labour, multiplied by the Mean Time To Repair (*MTTR*).

$$OPEX = Labour * MTTR + Spares * \frac{8766}{MTTF}. \tag{5}$$

In wave energy, the Yield is generally assessed as Annual Energy Production *AEP.* It is given by the expression in (6)

$$AEP = J * CL * \eta * 8766 * A, \tag{6}$$

In which *J* is the average wave energy flux, *CL* is the capture length of the technology under investigation, and *A* is the availability, estimated as a function of *MTTF* and *MTTR* as in (7).

$$A = \frac{MTTF}{MTTF + MTTR} \tag{7}$$

In (2)- (7), we have identified the functional dependencies among the different parameters and contributions that are part of the LCOE equation (1). By further refining the analysis of the LCOE, we have linked the different contributions to LCOE to the evaluation areas as defined in Section 2, a set of metrics (also named Evaluation Criteria in Section 2) and design parameters. The metrics are defined as quantitative measures used to assess technology; the design parameters are physical, mechanical, economic and project-related properties of the component that are directly or indirectly related to the different evaluation areas.

Two example graphs showing interconnections among evaluation areas, metrics and design parameters are reported in Figure 3.1 and Figure 3.2 for the LC and Yield, respectively.

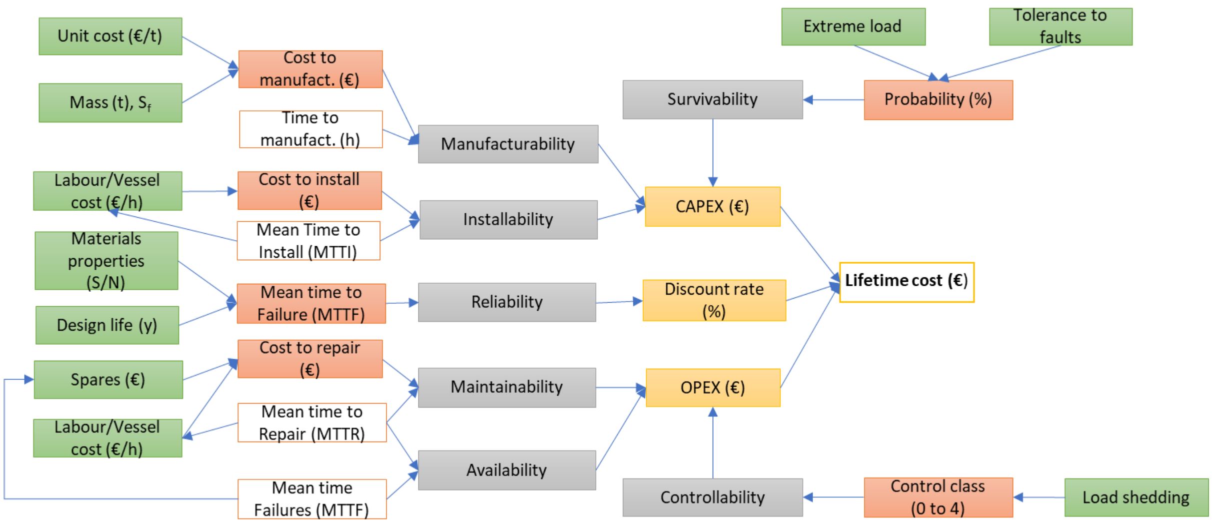

Figure 3.1: Graph of the logical connections among the Lifetime cost: the impact on the LCOE (in yellow), the Evaluation Areas (EAs) in grey, the metrics in red and the design parameters in green.

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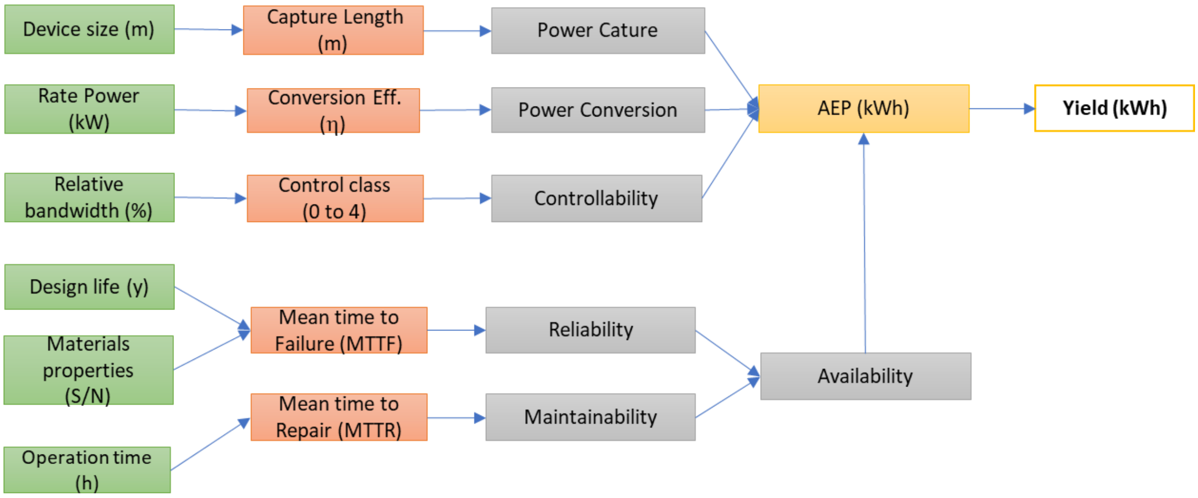

Figure 3.2: Graph of the logical connections among the Yield: the impact on the LCOE (in yellow), the Evaluation Areas (EAs) in grey, the metrics in red and the design parameters in green.

Those examples were offered to the technology developers during the workshops to explain the reverse engineering process for analysing their specific User Case. The purpose of this activity based on reverse engineering was to identify a set of metrics, design parameters and physical quantities to monitor during the hybrid test campaign to assess the improvements the experimental stage has allowed to obtain.

Aligned with these activities, an initial assessment of the status of their technology was done using the DTOceanPlus software.

These activities were held during a couple of workshops for each developer for every User Case. Some extra pending actions were carried out offline. The supporting spreadsheet for the stage-gate assessment using DTOceanPlus was presented online during the workshop held at DTU facilities in January 2023.

3.1.2 Outcomes

The initial results of T6.2 included the following:

- Identifying the **main Evaluation Areas** that the critical component for each User Case impacts most. As mentioned in Section 3.1.1, this outcome is the result of the reverse engineering approach carried out during the workshops with the developers.
- Concurrently, for each main evaluation area, the developers have suggested an **appropriate metric** to be monitored during the hybrid testing. The metric selection is based on the sensitivity with LCOE and the availability of direct measurements during the hybrid testing campaign that allow the continuous monitoring of the selected metric.
- For each relevant evaluation area, the developers have described the design parameters that impact the LCOE and the metric selected to monitor the behaviour of the critical component. The developers could define the design parameter and relevant units, and optionally they could suggest some values.
- Similarly, for each relevant evaluation area, the developers have described the space of **physically measured variables** during the hybrid test campaign. Only the measurements affecting the chosen metrics have been described; they were classified per evaluation area. Their description was completed in some cases with details such as units and operational values.

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- Given all the above, the users for each user case have provided some targets for the metrics before carrying out the test campaign in a qualitative fashion as (Low, Medium, High) impact or LCOE and, when possible, also in quantitative terms, by defining a value or a range of values.
- Finally, a **stage-gate assessment** of the technology using the DTOceanPlus toolset was carried outfor UC#2 and UC#3, focusing on the critical component's actual technology development status. In the case of UC#1, the outcome of D7.7 [13] of the project DTOceanPlus project is summarised. In that document, CorPower provided a stage-gate assessment of their technology (as for August 2021) at PTO level.

3.2 Workshops with the User Cases

3.2.1 The sessions

The activities in Task 6.2 were carried out in a hybrid format, alternating workshops involving the developers and offline work.

For each user case, two workshops of 1.5 hours duration each were held. In Table 3.1, there is the list of the sessions and the participants.

Table 3.1: List of the workshops for T6.2

Date	Title of the session	Participants
25/11/2022	UC#2 – Session 1	Patxi Etxaniz, Aimar Maeso, Jimmy Lee (IDOM), Julia F. Chozas (JFC), Pablo Ruiz-Minguela, Vincenzo Nava (TECNALIA)
20/12/2022	UC#2 – Session 2	Patxi Etxaniz, Aimar Maeso, Jimmy Lee (IDOM), Julia F. Chozas (JFC), Pablo Ruiz-Minguela, Vincenzo Nava (TECNALIA)
18/01/2023	UC#3 – Session 1	Steen Thomsen, Troels Lukassen (WavePiston), Julia F. Chozas (JFC), Pablo Ruiz-Minguela, Vincenzo Nava (TECNALIA), Bruno Sodiro, Daniele Bargiacchi (RINA)
23/01/2023	UC#1 – Session 1	Guillaume Unique, Antoine Bonel (CorPower), Julia F. Chozas (JFC), Pablo Ruiz-Minguela, Vincenzo Nava (TECNALIA), Bruno Sodiro, Daniele Bargiacchi (RINA)
13/02/2023	UC#1 – Session 2	Guillaume Unique, Antoine Bonel (CorPower), Julia F. Chozas (JFC), Pablo Ruiz-Minguela, Vincenzo Nava (TECNALIA), Bruno Sodiro, Daniele Bargiacchi (RINA)

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The second session with UC#3 was not held, given the difficulty of finding a common date. However, the forecast activity was carried out offline. For each user case, Session 1 dealt with the description of the Stage-Gate Framework, the overall activity description, identifying the most impacting evaluation area and the relevant metrics. Moreover, the discussion about the design parameters was engaged and completed offline. In Session 2, we explored the space of the physical variables impacting the metrics for each user case and the assessment of target values, which was therefore completed offline.

As for the stage-gate assessment using DTOceanPlus, we held an online session during the face-to-face workshop a the DTU facilities on January 25, 2023. Representatives from CorPower and WavePiston were present. The activities were described to IDOM later. IDOM and WavePiston then conducted the activity offline, while for UC#1 led by CorPower we have made reference to the outcome of D7.7 of the DTOceanPlus project.

3.2.2 Materials and methods

PowerPoint presentations and Microsoft Excel spreadsheets constituted the main documentation during the workshops.

- The **presentation** consisted of two major parts: a descriptive set of slides explaining the timing and the purpose of T6.2 and describing the stage-gate assessment process, the definitions of Evaluation Areas and metrics, the impacts of the critical components to LCOE as well as the examples of interconnections among LCOE, metrics and design parameters as shown in Figure 3.1 and Figure 3.2; and a section in which the interactive tasks involving the developers were explained. The interaction was carried out via a spreadsheet.
- The **spreadsheet** for the interactive parts of the sessions was the tool adopted to facilitate the bilateral workshops with the developers. The first tab, named "**Evaluation Areas and Metrics**", included the list of Evaluation Criteria and metrics from [2] and [12] for each Evaluation Area. During the first workshop, the most impacting Evaluation Areas were identified for each user case based on the reverse engineering approach described in Section 3.1.1. The metrics (one for each evaluation area) were selected. They were added if not included in the lists (see Figure 3.3). The second tab, "**Design parameters**", supported identifying design parameters. For each Evaluation Area of interest, one or more design parameters were identified, including some reference values, if available/possible and comments (Figure 3.4). Not all the Evaluation Areas were covered by all the User Cases, as they depended on the user ase itself. A third tab, "**Physical Variables**", filled during the workshop's second session, helped describe the measured quantities during the hybrid testing that could affect the LCOE (Figure 3.5), similar to the design parameters tab. A fourth tab, named "**Allocation of Targets**", supported the task of assigning, for all the metrics, a qualitative measure of the impact on LCOE and, optionally, the expected quantitative target value for the metric.

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Power Capture
Power captured [kW]
Capture length [m]
Annual captured energy [kWh]
Other

Power Conversion
Conversion efficiency [%]
Annual transformed energy [kWh]
Annual delivered energy [kWh]
Captured efficiency [%]
Relative transformed efficiency [%]
Relative delivered efficiency [%]
Other

Controllability
Category [0 - 4]
Other

Reliability
Failure rate (FR) [-]
Mean time to failure (MTTF) [hours]
Probability of failure [%]
Other

Survivability
Design conditions boundary [-]
Likelihood of exceeding an acceptable level of damage or loss of functionality [-]
Survival probabilities [%]
Other

Maintainability
Range of acceptable environmental conditions [-]
Mean Time To Repair (MTTR) [hours]
Repair rate (RR) [-]
Cost to repair [€]
Availability [%]
Maintenance probabilities [%]
Average maintenance duration [hours per kW per year]
Other

Installability
Range of acceptable environmental conditions [-]
Mean Time To Install (MTTI) [hours]
Transit speed [knots]
Cost to install [€]
Installation duration [hours per kW]
Other

Manufacturability
Manuf Readiness Level (MRL) [1 - 10]
Time to Manufacture [hours]
Cost to manufacture [€]
Other

Affordability
CAPEX [€]
OPEX [€/year]
LCOE [€/kWh]
CapEx per kW [€/kW]
OpEx per kW per year [€/kW per year]
IRR [%]
Other

Acceptability
Global warming potential (GWP) [gCO2/kWh]
Cumulative energy demand (CED) [kJ/kWh]
Energy payback period [months]
Jobs created [-]
Global negative EIA [-]
Global positive EIA [-]
Cost of consenting [€]
Other

Figure 3.3: Evaluation Areas, criteria and metrics in the supporting spreadsheet (from [2] and [12]).

Evaluation Area	Design Parameter	Design Value (Optional)	Comments
Power Capture			
Power Conversion			
Controllability			
Reliability			
Survivability			
Maintainability			
Installability			
Manufacturability			
Affordability			
Acceptability			

Figure 3.4: Design Parameters tab of the supporting spreadsheet.

Evaluation Area	Physical Variable	Range (Optional)	Comments
Power Capture			
Power Conversion			
Controllability			
Reliability			
Survivability			
Maintainability			
Installability			
Manufacturability			
Affordability			
Acceptability			

Figure 3.5: Physical Variables tab of the supporting spreadsheet.

Evaluation Areas Selected	Metrics Selected	Target Value	Impact on LCOE (Qualitative)	Comments
Power Capture				
Power Conversion				
Reliability				
Survivability				
Maintainability				
Affordability				

Figure 3.6: Allocation of Targets tab of the supporting spreadsheet.

As for the Stage-Gate Assessment, we have used the Stage-Gate module of the **DTOceanPlus** platform. We have limited the Stage-Gate Assessment only to the **Activity checklist** (see the manual of the Stage-Gate tool for a complete description of the features of this tool [14]).

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The Stage-Gate Tool in DTOceanPlus is a useful tool to i) provide a framework to assess ocean energy technology (arrays, devices and subsystems), ii) facilitate clear, consistent assessment, and iii) enable technology developers to demonstrate success. The tool consists of several functionalities. In T6.2 of VALID, we have focused on running the Activity checklist feature. The Activity Checklist supports the technology developer in identifying the development activities completed and grouped for evaluation areas. This will help assess the technology readiness level in the different evaluation areas and highlight the outstanding activities required to complete a specific stage. In order to facilitate the user developers tasks, we have used a supporting spreadsheet for identifying, at each stage, the activities carried out for each evaluation area. This procedure avoided the installation of the DTOceanPlus software and smoothed the process. The data were therefore uploaded to DTOceanPlus by TECNALIA, and the standardised reports were generated. As major comments towards the DTOceanPlus software, two improvements were identified; first of all, the developers found the questions oriented to the level of aggregation “device”, i.e. the questions were difficult to adapt for the component level of aggregation. Another comment was that the manufacturing phase was not accounted for in the Stage-Gate tool in DTOceanPlus.

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4 Stage-gate assessment for UC1

4.1 Overview

User Case #1 deals with the Point Absorber device for wave energy conversion developed by CorPower. The device is connected to the seabed using a tensioned mooring line, moving in resonance with incoming waves, making it move in and out of the water surface, thanks to a combination of pretension and the WaveSpring technology (see Figure 4.1). The critical components investigated in VALID are the dynamic seals of the piston chamber sealing system in CorPower PTO (see Figure 4.2). The dynamic sealing systems can be exposed to severe conditions and subject to complex physical interactions between housings, sliding surfaces, sealing components, lubrication media and the external environment

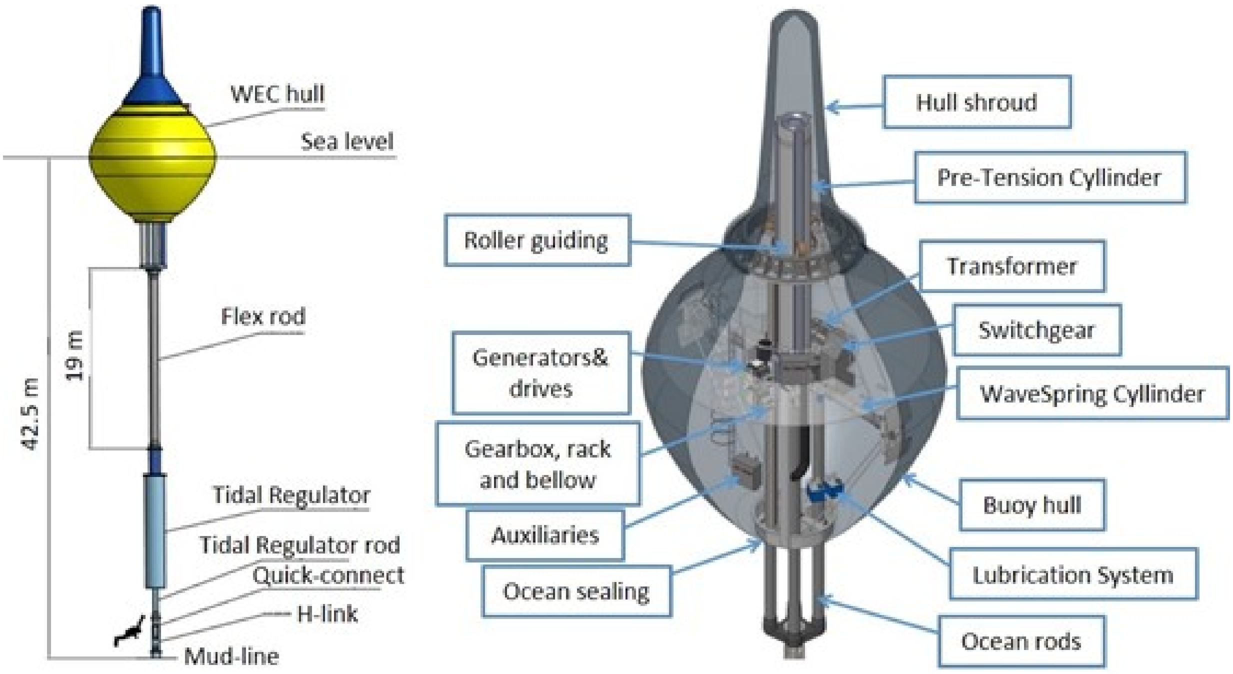

Figure 4.1: The CorPower WEC and subsystem overview.

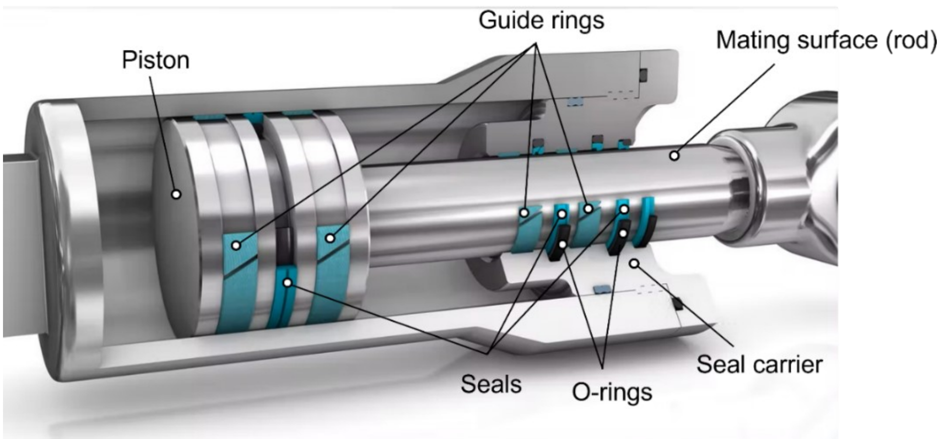

Figure 4.2: Illustration of a typical piston chamber sealing system.

The objective of UC#1 is to fully characterise the sealing under a range of speeds and accelerations, with consideration for degradation mechanisms such as wear, fatigue at joints, corrosion, tribocorrosion, and biofouling using a customised test rig specifically designed to test dynamic sealing systems, see Figure 4.3

Figure 4.3: The CorPower dynamic seal test rig.

Further details on the CorPower test rig and the test plan devised in UC#2 are reported in D3.1 [15].

4.2 Key metrics

During the first session with CorPower, the Evaluation areas and the inherent metrics identified as interesting for UC#1 are compiled in Table 4.1.

Table 4.1: Relevant Evaluation Areas and Criteria/Metrics for UC#1.

Evaluation Areas	**Evaluation Criteria / Metrics [units]**
Reliability	Mean time to failure (MTTF) [hours]
Maintainability	Mean Time To Repair (MTTR) [hours]
Affordability	OPEX [€/year]

The final decision on the most relevant Evaluation Areas and metrics derived from the discussions during the first workshop. In detail, the following considerations were listed:

- The critical component does not impact directly on many Evaluation Areas, but in some cases, it does it indirectly. For example, in terms of Power Capture, the control law (and therefore, Controllability) relies on some dynamic seals and can increase the power capture.
- Acceptability may have a direct or indirect impact, such as using higher performance lubricants to reduce friction and the increase of noise due to friction, but that might have lower environmental performance (for example, less biodegradable). However, in both cases, they are difficult to quantify.
- Manufacturability, Installability and Power Conversions (regarding efficiency) are less important.
- Survivability is indirectly guaranteed by the use of seals and valves.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

4.3 Design parameters

Among the design parameters that characterise the dynamic seals for the CorPower technology, the ones that affect the Evaluation Areas identified in Table 4.1 are reported in Table 4.2. For some of the design parameters, CorPower suggested some typical design values; in some other cases, it was not possible due to confidentiality or because they are strongly dependent on the specific application.

Table 4.2: Relevant Design parameters with values for UC#1.

Evaluation Areas	Design parameter [units]	Design Value (Optional)
Reliability	Stroke length [m]	8
Reliability	Rod surface roughness [mm]	
Reliability	Oil viscosity [Pa.s]	
Reliability	O-ring compression rate [%]	> 10%
Reliability	Seal redundancy [-]	
Reliability	Cooling capacity [W]	
Maintainability	Maintenance strategy [-]	
Maintainability	Operation time [h]	
Affordability	Vessel cost [€/day]	

The general considerations that led to shortlisting the selection of design parameters were:

- Several design parameters (surface roughness, viscosity of the oil, o.ring compression rate) can indirectly affect friction forces and wear rates.
- Maintenance strategy is critical, being offshore repairs particularly costly; preventive/predictive strategies based on inspections, continuous monitoring and fault detection identification and detection of anomalies should be preferred to reduce the time of the operations.

4.4 Physical variables

Among the physical variables measured during the testing campaign in VALID for UC#1, the ones that affect the Evaluation Areas identified in Table 4.1 are reported in Table 4.3. Similarly to Table 4.2, CorPower has provided some typical ranges of values for some of the physical variables to be measured; in some other cases, this was not possible due to confidentiality reasons or because those values depend on the specific application.

Table 4.3: Relevant Physical variables with values for UC#1.

Evaluation Areas	Physical Variables [units]	Range (Optional)
Reliability	Total travelled distance for the seals [m]	108 / 5
Reliability	Number of turning points [-]	
Reliability	Pressure [bar]	100 - 300
Reliability	Temperature [ºC]	0 - 80
Reliability	Friction force [N]	

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Reliability	Speed [m/s]	4 - 5
Reliability	Acceleration [m/s2]	
Reliability	Lubrication flow rate [mm3/stroke]	
Reliability	Normal force [N]	4000
Reliability	Air leakage rate [kg/h]	
Reliability	Vibration [Hz]	
Maintainability	Pressure [MPa]	
Maintainability	Temperature [ºC]	

All the physical variables measure one or more metrics identified in Table 4.1. Measures of the seals travelled distance, the temperature, the pressure, the speed or the friction force can indirectly detect anomalies and monitor degradation and failure.

4.5 Targets

Based on the design characteristics of the dynamic seals in Table 4.2 and the measurements in Table 4.3, some targets on the metrics in Table 4.1 were established during the workshop's second session. The impact on LCOE is reported in Table 4.4. CorPower has not declared any Target Value for the metrics.

Table 4.4: Metrics and their impact on LCOE for UC#1.

Evaluation Criteria / Metrics [units]	Target values	Impact on LCOE
Mean time to failure (MTTF) [hours]		High
Mean Time To Repair (MTTR) [hours]		High
OPEX [€/year]		High

Even if the MTTF is the chosen metric for Reliability, the total travel distance of the piston and number of turning points physically affect and define the components failure rates.Due to the complex nature of sealing systems, a full degradation model of the dynamic seals is not elaborated yet, but according to CorPower, building a more detailed, multiphysics model to estimate the remaining useful life of the seals is one of the outcomes of the VALID project for UC#1.

4.6 Stage-Gate Assessment

CorPower has not carried out the stage-gate assessment of the critical component using DTOceanPlus since they participated in the DTOceanPlus project and contributed by running some validation scenarios in 2021. In particular, in the D7.7 [13] in DTOceanPlus, entitled "Demonstration results of integrated design tools for Wave Energy", CorPower ran the Validation Scenario VS 2 for Wave Energy Converters, whose objective was to carry out a stage-gate assessment for a PTO using the Stage-Gate design tool and produce a report for the developer to demonstrate their performance.

Although the aim of the D7.7 in DTOceanPlus and the scope of the present deliverable are slightly different, we have included a summary of the outcome of that task as publicly documented. It must be noted that the results of D7.7 in DTOceanPlus correspond to the activities accomplished by September 2021. Therefore, the latest innovations in CorPower technology could not be eventually taken into account.

In VS 2, CorPower assessed their PTO in an array context. They assessed the stage at which their technology is by estimating the LCOE(€/kWh) to prove and highlight any areas that could not be assessed with a link to the Structured Innovation tool for further development.

The user case for this scenario included running the stage-gate assessment as an array. However, the 10MW array scenario could not be run due to lack of time, so they carried out the assessment only considering a single device. In VS2, CorPower ran the Activity Checklist in the Stage-Gate and some Deployment and Assessment Design tools.

The outcome of the Activity Checklist was documented in Section 5.1.4.1 of D7.7. From the Activity checklist diagram (see Figure 4.4), all the activities to be assessed up to Stage 3 were completed, so D7.7 CorPower technology was a Stage 4 of development in September 2021.

Figure 4.4: Completed activities at the different stages for UC#1 (from D7.7 of DTOceanPlus).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006927.

5 Stage-gate assessment for UC2

5.1 Overview

User Case #2 deals with the Oscillating Water Column (OWC) device for wave energy conversion developed by IDOM. The critical component investigated is the Power Take-Off system's generator, i.e. the PTO's electrical component, which transforms mechanical power into electrical power. It interacts with the primary PTO (in this User Case, an air turbine), with power electronics and the control system, to deliver electrical power to the grid (see Figure 5.1). The focus is to investigate the **generator's thermal fatigue life,** particularly the **stator windings** insulation.

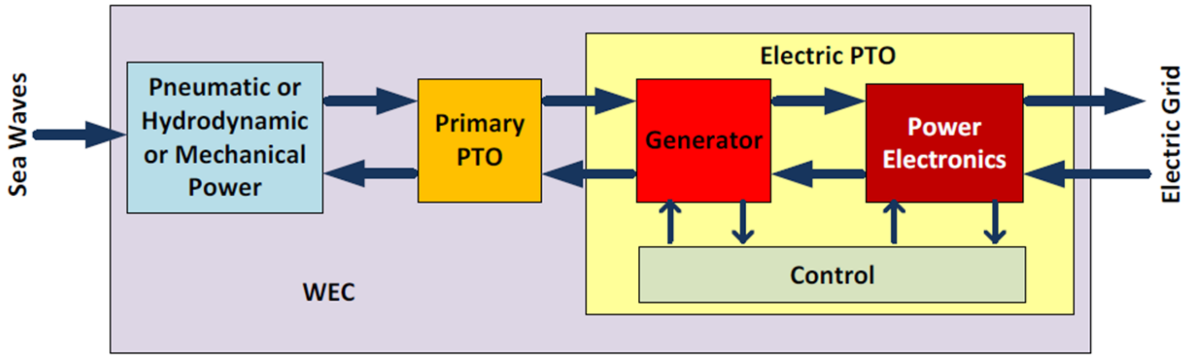

Figure 5.1: Wave-to-wire model of a generic Wave Energy Converter (WEC).

UC#2 hybrid testing procedure is based on a Hardware-in-the-Loop (HIL) test methodology at the "Electrical PTO Lab" in the test rig at TECNALIA. The equipment consists of a mixture of physical devices representative of the actual components of the WEC (that is, generator, power electronics, control system), lab-scale equipment (that is, the electrical motor with dedicated inverter and control software which reproduce the mechanical loads produced by the air chamber and turbine in the actual WEC) and numerical models (that is, the sea states). Further details on the Electrical PTO Lab and the test plan devised in UC#2 are reported in D4.2 [16] (see Figure 5.2).

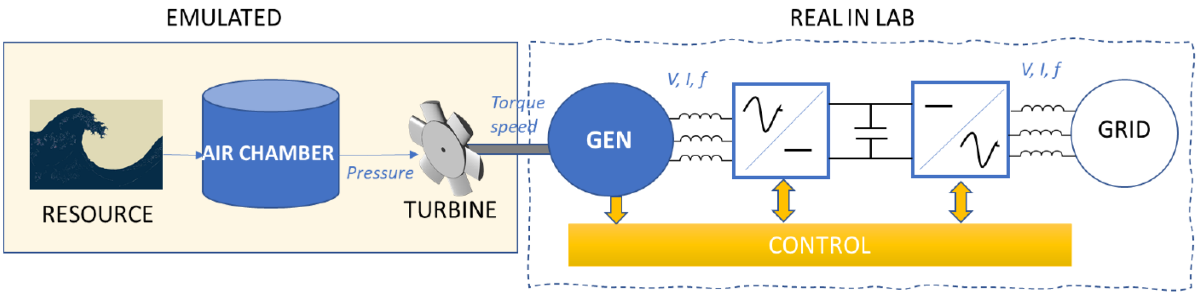

Figure 5.2: Schematic view of the emulated, virtual, and "real" or physical components in the hybrid test rig Electrical PTO Lab at TECNALIA.

5.2 Key metrics

During the first session with IDOM, the Evaluation areas and the inherent metrics identified as interesting for UC#2 are recompiled in Table 5.1.

Table 5.1: Relevant Evaluation Areas and Criteria/Metrics for UC#2.

Evaluation Areas	Evaluation Criteria / Metrics [units]
Power Capture	Annual Captured Energy [kWh]
Power Conversion	Conversion efficiency [%]
Reliability	Mean time to failure (MTTF) [hours]
Survivability	Likelihood of exceeding an acceptable level of damage or loss of functionality [-]
Maintenaibility	Mean Time To Repair (MTTR) [hours]
Affordability	LCOE [€/kWh]

The final decision on the most relevant Evaluation Areas and metrics derived from the discussions during the first workshop. In detail, the following considerations were listed:

- Strictly considering the critical subsystem of UC#2, i.e. the generator, power capture has an indirect impact, and somehow it is interrelated with reliability, as extending the range of sea states with a PTO working will increase the captured energy.
- The generator's efficiency is affected by its scale, as, in general, a lower-rated power generator will increase its performance in terms of efficiency. However, this could conflict with maximising the power capture.
- Survivability is important; some design decisions as the usage of butterfly valves (to protect the PTO from floodings or development of high temperatures), the control strategies or the redundancy in the number of generators, will allow the assignment of stringent values for the associated metrics.
- The role played by the maintenance strategy is particularly relevant; monitoring the components and assessing their health status, and converting corrective maintenance strategies into preventive and predictive ones has an important economic impact. Similarly, reducing the repair time or repairing the components in situ or at the harbour definitively affects the LCOE
- In terms of Affordability, it is convenient to consider an aggregated metric.
- Controllability, installability, manufacturability and acceptability either have a low impact, i.e. the design decisions for the generator do not alter these areas significantly, or could be accounted for by considering other evaluation areas.

5.3 Design parameters

Among the design parameters that characterise the generator for the IDOM technology, the ones that affect the Evaluation Areas identified in Table 5.1 are reported in Table 5.2. For some of the design parameters, IDOM suggested some typical design values; in some other cases, it was not possible due to confidentiality or because they are strongly dependent on the specific application.

Table 5.2: Relevant Design parameters with values for UC#2.

Evaluation Areas	Design parameter [units]	Design Value (Optional)
Power Capture	Cut-out sea state (Hs) [m]	5

Power Capture	Rated power [kW]	
Power Conversion	Efficiency curve at partial loads (P/Prated) [-]	
Power Conversion	Rated power [kW]	
Reliability	Design life [year]	2
Reliability	Redundancy level (no. of generators n) [-]	4
Survivability	Maximum to Nominal Voltage [-]	3
Survivability	Response time of the butterfly valve [s]	
Survivability	Acceptable no of failed generators k (k/n)	k = n-1
Maintainability	Replacement time [hour]	<8
Maintainability	Maintenance vessel cost [€/day]	
Maintainability	Maintenance strategy [-]	Calendar based
Affordability	Generator mass [kg]	
Affordability	Unit cost [€/kW]	
Affordability	Maintenance vessel cost [€/day]	

The general considerations that led to shortlisting the selection of design parameters were:

a. Increasing the range of operational conditions based on the understanding of the behaviour of the generator under voltage peaks could lead to an increase in power capture and assess its survivability.
b. Redundancy in terms of the total number of generators and the percentage of failed generators affect both the reliability and the survivability of the system at the device level;
c. A maintenance strategy is considered to be one of the most relevant cost drivers;
d. The cost of the generator has a relatively small impact on the global LCOE, so the mass of the generator should be considered more as an impact on the OPEX rather than on the CAPEX.

5.4 Physical variables

Among the physical variables measured during the hybrid testing in VALID, the ones that affect the Evaluation Areas identified in Table 5.1 are reported in Table 5.3. IDOM did not provide any range for the physical variable due to confidentiality reasons and because in some cases they are dependent on the specific application.

Table 5.3: Relevant Physical variables with values for UC#2.

Evaluation Areas	**Physical Variables [units]**	**Range (Optional)**
Power Capture	Operating Limit Condition - Sea State [Hs, m]	
Power Conversion	Supplied energy (driving motor) [kWh]	

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Power Conversion	Generated energy (output) [kWh]	
Reliability	Voltage [V] & Current [A]	
Reliability	Efficiency [%]	
Reliability	Winding Resistance [Ohm]	
Reliability	Winding Temeprature [ºC]	
Reliability	Case vibration [Hz; mm/s]	
Reliability	Standard ambient conditions [various]	
Reliability	Operating Limit Condition - Sea State (Hs) [m]	
Survivability	Maximum Voltage [V] & Current [A]	
Maintainability	Estimated cumulative damage [%]	
Affordability	n/a	

All the physical variables are used to measure one or more metrics identified in Table 5.1, such as the generated energy, to assess the efficiency. Some of these measurements, such as changes in the efficiency, resistance and temperature of the windings or the vibration of the case, can serve as an indirect measurement for the degradation. The external conditions such as salinity and humidity may impact the generator's reliability, even though it is very difficult to measure them and even more difficult to reproduce them in a controlled environment. No direct measure can be obtained to assess the affordability.

5.5 Targets

Based on the design characteristics of the generator in Table 5.2 and the measurements in Table 5.3, during the workshop's second session, some targets on the metrics in Table 5.1 were defined using a very simplified LCOE model. The impact on LCOE and target values are reported in Table 5.4

Table 5.4: Metrics and their impact on LCOE for UC#2.

Evaluation Criteria / Metrics [units]	Target Values	Impact on LCOE
Annual Captured Energy [kWh]	1.9e6	Low
Conversion efficiency [%]	60%	High
Mean time to failure (MTTF) [hours]	8406	Medium
Likelihood of exceeding an acceptable level of damage or loss of functionality [-]	0%	High
Mean Time To Repair (MTTR) [hours]	360	Medium
LCOE [€/kWh]	0.15	Medium

It is relevant to notice that the threshold of occurrence of critical damage was set to a very low level (0%) while defining the reference values given its impact on LCOE.

5.6 Stage-Gate Assessment

The Activity Checklist for the stage-gate assessment using the DTOceanPlus software was done carried out for all the Evaluation Areas, despite the ares identified as important in Table 5.1 were Power Capture, Power Conversion, Reliability, Survivability, Maintenaibility, and Affordability. Moreover, IDOM also filled the area of Controllability. the global results regarding shares of completed activities per stage are shown in Figure 5.3. However, it was identified as a limit and a potential improvement for DTOceanPlus the option to fill the Activity checklist survey only for some evaluation areas and then to disaggregate the global results, not accounting in the global results for the unfilled evaluation areas.

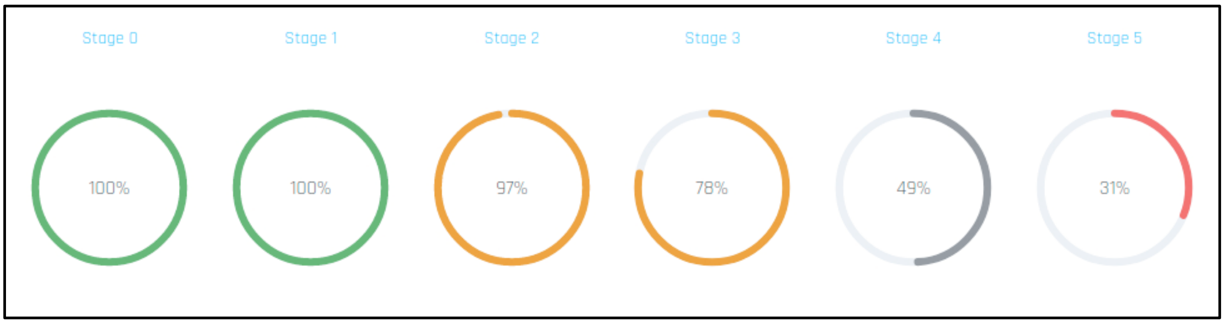

Figure 5.3: Completed activities at the different stages for UC#2.

Activities are fully completed at Stage 0 and Stage 1.

At Stage 2 (see Figure 5.4), the only activity not completed is "Estimate of impact on LCOE of damage or loss of functionality and implementation of protective action (cost of required systems and reduced availability) supported by outputs of modelling, testing and design". This lead to a 97% fulfilment of activities (37 activities out of a total of 38 activities).

Figure 5.4: Completed activities at Stage 2 per Evaluation Area in UC#2.

In Figure 5.5 and Figure 5.6, there are reported bar diagrams for Stages 3 and 4, respectively. At Stage 3, in all the evaluation aras some activities were carried out, achieving a 78% of fulfilment of the activities for the stage (32 activities out of a total of 41 activities). It is noteworth that at Stage 3 all the activities related to Installability, Power Capture, Power Conversion and Contorllability were carried out.

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Figure 5.5: Completed activities at Stage 3 per Evaluation Area in UC#2.

At Stage 4, the total number of activities was not fulfilled in any area. No activities of the EA of Acceptability were carried out. Almost half of the activities (49%) at this stage were carried out (21activities over a total of 43).

Figure 5.6: Completed activities at Stage 4 per Evaluation Area in UC#2.

At Stage 5, no activities for Acceptability and Installability were carried out. The area in which most of the activities are carried out at this stage is Power Conversion. Globally, a percentage of fulfilment of activities of 31% is achieved, with 15 activities out of 43 completed.

Figure 5.7: Completed activities at Stage 5 per Evaluation Area in UC#2.

Given the level of achievements and based on the critical component and the Evaluation Area considered, we consider that IDOM, before the hybrid testing in VALID and at the time of writing, has almost completed Stage 2 of development, and it is well advanced at Stage 3. In the Annex, we included the standardised report generated by DTOceanPlus at Stage 3.

6 Stage-gate assessment for UC3

6.1 Overview

The WEC developed by WavePiston is the main objective of user case #3 in the VALID project. It consists of an oscillating surge wave energy converter (OSWEC) with multiple bodies and comprises surging plates connected by beams. Two telescopic hydraulic pumps are connected to a cart that each plate mounted. An Energy Collector (EC) comprises a plate, wagon, EC beam, and pumps (Figure 6.1). A chain of up to 32 connected ECs will make up the WavePiston WEC. The hydraulic pumps in the ECs push seawater into a transport pipe. The pipe leads the pressurised water to an onshore turbine and/or a reverse osmosis system.

In UC#3, therefore, the critical component for reliability is the seawater hydraulic pump seals used in OSWEC. The seals are typically found in the power-take-off (PTO) subsystems. The wear of the hydraulic seals has been identified as a critical factor for the WavePiston device. The seals are a vital system part for the WavePiston OSWEC as the hydraulic pumps generate power and (i) make the ECs self-centring, and (ii) are vital for the structure's integrity by providing damping for the motion of the wagon.

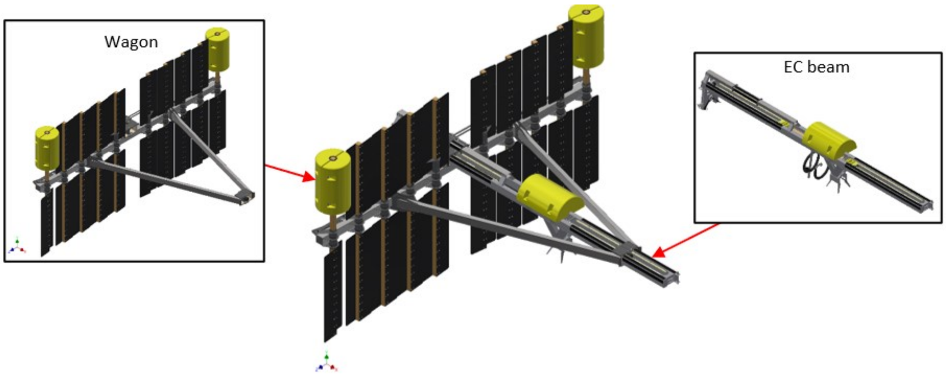

Figure 6.1: The WavePiston floating oscillating surge wave energy converter.

In the VALID hybrid testing approach, numerical and analytical models emulate some parts of the WavePiston OSWEC. At the same time, the seals will be represented in the physical test rig. The numerical and physical models for User Case #3 are presented in Figure 6.2.

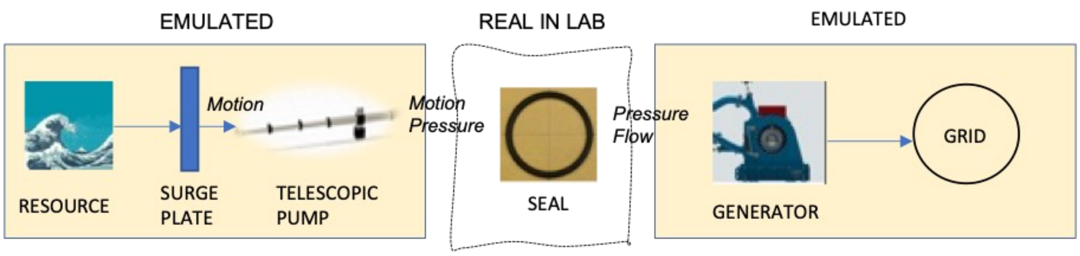

Figure 6.2: Emulated vs real subsystems in the VALID hybrid testing approach for seawater hydraulic seals.

Further details on the hybrid test rig and the test plan devised in UC#3 are reported in D5.1 [17] and D5.2 [18].

6.2 Key metrics

During the first session with WavePiston, the Evaluation Areas and the inherent metrics identified as interesting for UC#3 are recompiled in Table 6.1.

Table 6.1: Relevant Evaluation Areas and Criteria/Metrics for UC#3.

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Evaluation Areas	Evaluation Criteria / Metrics [units]
Power Conversion	Conversion efficiency [%]
Reliability	Mean Time To Failure (MTTF) [hours]
Maintainability	Mean Time To Repair (MTTR) [hours]
Installability	Mean Time To Install (MTTI) [hours]
Manufacturability	Cost to manufacture [€]
Affordability	CAPEX [€]

The final decision on the most relevant Evaluation Areas and metrics derived from the discussions during the first workshop. In detail, the following considerations were considered:

- Some Evaluation Areas, such as Power capture, are coupled with others, such as Power Conversion.
- For some areas, the metrics associated with Evaluation Area are also related to some design parameters and physical variables. For example, the Reliability is strictly connected to the redundancy of the pumps.
- Also, for UC#3, the Maintainability is governed by choice of an appropriate maintenance strategy, being onsite Maintenance based on a predictive or preventive approach to be preferred.
- Manufacturability is key for UC#3, being the component expensive because of the materials (i.e. it is not the process itself to be expensive).
- Acceptability is an important area, but its impact is difficult to be measured.

6.3 Design parameters

Among the design parameters that characterise the generator for the WavePiston technology, the ones that affect the Evaluation Areas identified in Table 6.1 are reported in Table 6.2. For some of the design parameters, WavePiston suggested some typical design values; in some other cases, it was not possible due to confidentiality or because they are strongly dependent on the specific application.

Table 6.2: Relevant Design parameters with values for UC#3.

Evaluation Areas	Design parameter [units]	Design Value (Optional)
Power Conversion	Pressure [MPa]	2-8
Power Conversion	Surface finish [mm]	N/A
Reliability	Design life [year]	7
Reliability	Redundancy level (no. EC's per string) `-]	24-32
Survivability	Check valve [-]	1 per pump
Maintainability	Maintenance strategy [-]	Preventive - every 7 year
Maintainability	Vessel cost [€/day]	app. 5000

Maintainability	Operation time [h]	<1
Installability	Vessel cost [€/day]	app. 5000
Installability	Operation time [min]	<10
Manufacturability	Manufacturing unit cost [€]	The costs of seals are negligible
Affordability	Power to mass [kW/kg]	N/A

The general considerations that led to shortlisting the selection of design parameters were:

- Regarding reliability, a target lifetime of the seals is considered to be 7 years. Seals do not have to be completely tight; up to 5% leakage is acceptable. Higher leakage reduces the efficiency of the individual pump but is not a critical failure. The lifetime of seals is tested in an accelerated test where the leakage is monitored. Redundancy is achieved via 24-32 independent EC's (each with 2 independent pumps) on a string.
- In terms of maintenance, an easy detachment of EC modules should be guaranteed. Replacement of seals in pumps requires that the EC's are disassembled on a vessel deck.

6.4 Physical variables

Among the physical variables measured during the hybrid testing in VALID, the ones that affect the Evaluation Areas identified in Table 6.1 are reported in Table 6.3. WavePiston suggested some optimal ranges of values for most of the physical variables to be monitored during the testing. In other cases, this was not possible as they were difficult to quantify, or for confidentiality issues.

Table 6.3: Relevant Physical variables with values for UC#3.

Evaluation Areas	Physical Variables [units]	Range (Optional)
Power Conversion	Water leaking [%]	<5
Power Conversion	Friction [kN]	<1
Reliability	Pressure drop [kPa]	
Reliability	Water leaking [%]	<
Maintainability	MTTR Disassemble pumps [hours]	>1
Installability	Seals are preassembled in pumps [-]	
Manufacturability	Use of Standard seals [-]	
Affordability	Cost [€]	<100
Acceptability	Lifetime [years]	>7

6.5 Targets

Based on the design characteristics of the generator in Table 6.2 and the measurements in Table 6.3, during the workshop's second session, some targets on the metrics in Table 6.1

were defined using a very simplified LCOE model. The impact on LCOE and target values are reported in Table 6.4

Table 6.4: Metrics and their impact on LCOE for UC#3.

Evaluation Criteria / Metrics [units]	**Target Values**	**Impact on LCOE**
Conversion efficiency [%]	>95%	Medium
Mean Time To Failure (MTTF) [hours]	>80.000	High
Mean Time To Repair (MTTR) [hours]	>60.000	High
Mean Time To Install (MTTI) [hours]	<0,1	Low
Cost to manufacture [€]	<100€	Low
CAPEX [€]	<110€	Low
OPEX [€/year]	<150€	High

All the values for MTTI and costs are referred to for the EC module.

6.6 Stage-Gate Assessment

The Activity Checklist for the stage-gate assessment using the DTOceanPlus software was done only for the Evaluation Areas identified as important in Table 6.1, namely Power Conversion, Reliability, Maintainability, Installability, Manufacturability and Affordability. Manufacturability, however, is not one of the Evaluation Areas analysed in DTOceanPlus. However, WavePiston has been considered useful for filling the activity checklist for the activities in the other areas, such as Controllability, Power Capture and Acceptability. This somehow biased the global results regarding shares of completed activities per stage, as shown in Figure 6.3.

Figure 6.3: Completed activities at the different stages for UC#3.

WavePiston has considered that all the activities are completed until Stage 2.

In Figure 6.4 and Figure 6.5, there are reported bar diagrams for Stages 3 and 4, respectively. At Stage 3, only the terms of Reliability and Affordability activities are fully completed. On the contrary, the activities in terms of Power Capture and Controllability are less completed; however, those Evaluation Areas are not affecting the behaviour of the critical component. If we considered only the Evaluation Areas affected by the critical component, the total of completed activities increases up to 23 out of a total of 28, with a percentage of coverage equal to 82%

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Figure 6.4: Completed activities at Stage 3 per Evaluation Area in UC#2.

At Stage 4 (Figure 6.5), the total number of activities was fulfilled only regarding Affordability. Considering only the Evaluation Areas affected by the critical component of WavePiston, the percentage of fulfilment of the activities decreases up to 31% (9 activities over a total of 29), with respect to the 35% in Figure 6.4.

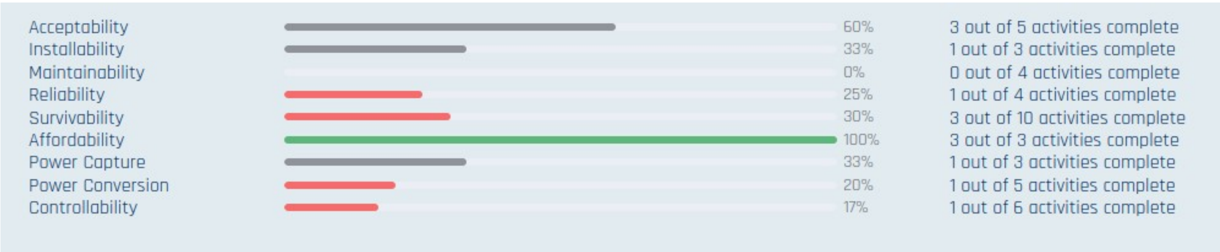

Figure 6.5: Completed activities at Stage 4 per Evaluation Area in UC#3.

At Stage 5 (Figure 6.6), none of the activities for the Evaluation Areas of Installability and Power Conversion is completed, while the ones pertinent to Affordability are fully completed.

Figure 6.6: Completed activities at Stage 5 per Evaluation Area in UC#3.

Given the level of achievements and based on the critical component and the Evaluation Areas considered, we consider that WavePiston, before the hybrid testing in VALID and at the time of writing, has completed Stage 2 of development, and the achievement of Stage 3 is ongoing. For this reason, we include in the Annex the standardised report generated by DTOceanPlus corresponding to Stage 3.

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research and innovation programme under grant agreement No 101006927.

7 Concluding Remarks and Future Work

In D6.3, we have reported the activities developed in T6.2 until the time of writing. This activity in the VALID project aims at setting a reference for the stage-gate evaluation of **critical components** for the three User Cases studied in the project: the dynamic valves for the CorPower WEC (UC#1), the generator for the IDOM OWC (UC#2); and the seals for the WavePiston OSWEC (UC#3). It is important to underline the significant difference with the work done within T6.3, primarily focused on the techno-economic analysis of the whole holistic system at the device level.

We carried out a **hybrid approach** during the development of this task, alternating **workshops** held remotely with **offline work**. During this activity, we had the chance to investigate further the main Evaluation Areas that the different critical components in the UCs affect for estimating the LCOE. A main **metric** describes each **Evaluation Area**. Moreover, the main **design parameters** and the **physical variables** measured during the hybrid test campaigns were identified during the workshops. These parameters are particularly relevant because they affect the metrics monitored during the test campaign and the LCOE. To this purpose, the wave energy developers have also identified some target values for these metrics, when possible, and their impact (low, medium, high) on the LCOE. For two of the UCs (namely, UC#2 and UC#3), the wave developers have also run the **Activity Checklist** tool of the **Stage-Gate** module in **DTOceanPlus** to assess the development status of the critical components objectively. In both cases, for the Evaluation Areas considered of most importance, the components have fully achieved a Stage equal to 2 and are at finalising Stage 3 of development. We include in the Annex the standardised reports at Stage 3. In UC#1, we have referred to the stage-gate Assessment done by CorPower during the project DTOceanPlus in August 2021. At that time, the component PTO achieved the Stage 4.

Some improvements to the DTOceanPlus are also suggested, such as the possibility of running the Activity Checklist only for some areas (and the results are biased by the activities in the Evaluation Areas that have not been considered to be impacted by the critical components); moreover, the questions seem more oriented towards the devices as a level of aggregation; finally the manufacturability is not considered as Evaluation Area.

Activity T6.2 is ongoing, and the outcome will be documented in D6.5. The following steps are:

- **Collect experimental hybrid testing results** from WP3-4-5 for the three UCs
- **Assess progress on critical metrics**, checking how the hybrid testing and the Stage-gate process have affected the processes.
- **Draw valuable recommendations** for other developers.

8 Nomenclature

Abbreviations

A	Availability
AEP	Annual Energy Production
CL	Capture Length
CAPEX	Capital Expenditure
DTU	Technical University of Denmark
EA	Evaluation Area
EC	Energy Collector
EU	European Union
FCR	Fixed Charge Rate
HIL	Hardware in the Loop
HMRC	Hydraulics and Maritime Research Centre (Ireland)
IEA- OES	International Energy Agency – Ocean Energy Systems
IEC	International Electrotechnical Commission
J	Wave energy flux
LC	Lifetime Costs
LCOE	Levelized Cost of Energy
MRL	Manufacturing Readiness Level
MTTF	Mean Time to Failure
MTTI	Mean Time to Install
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
OPEX	Operational Expenditure
OSWEC	Oscillating Surge Wave Energy Converter
OWC	Oscillating Water Column
PTO	Power Take Off
SG	Stage Gate
TRL	Technology Readiness Level
UC	User Case
WEC	Wave Energy Converter
WES	Wave Energy Scotland

9 References

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Annex 1

In this Annex, the two standardised reports generated using DTOceanPlus are included. The reports include only the Activity checklist using the Stage-Gate tool at Stage 3 for the critical components in UC#2 and UC#3.

Stage Gate Design Tool

Summary report

VALID - UC#2_sg

Stage Gate v1.0.0
16/04/2023

TABLE OF CONTENTS

The following requested sections have been included in this summary report;

INTRODUCTION

This report is an output of the DTOceanPlus Stage Gate design tool. The aim of this report is to assist decision-making through standardised activities, questions and metrics to assess ocean technology development process in objective assessment. For more details on how the Stage DTOceanPlus website or through the Graphical User Interface (GUI) of the software.

STUDY DETAILS

The summary details of the Stage Gate study being assessed are given below:

- Name: VALID - UC#2_sg
- Description:
- Threshold settings: Default (no metric thresholds)
- Selected Stage: Stage 3
- Selected Stage Gate: N/A

ACTIVITY CHECKLIST RESULTS

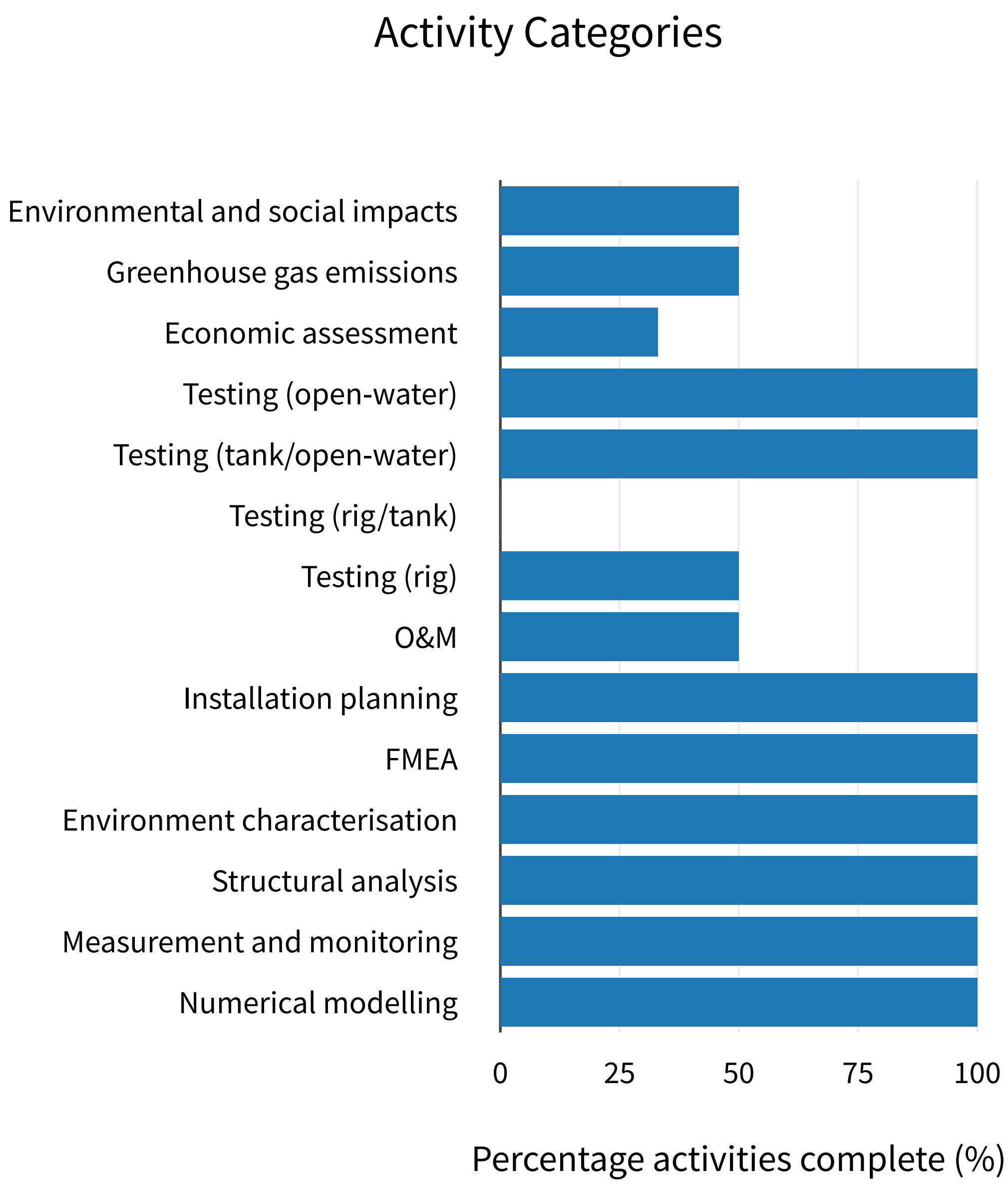
SUMMARY

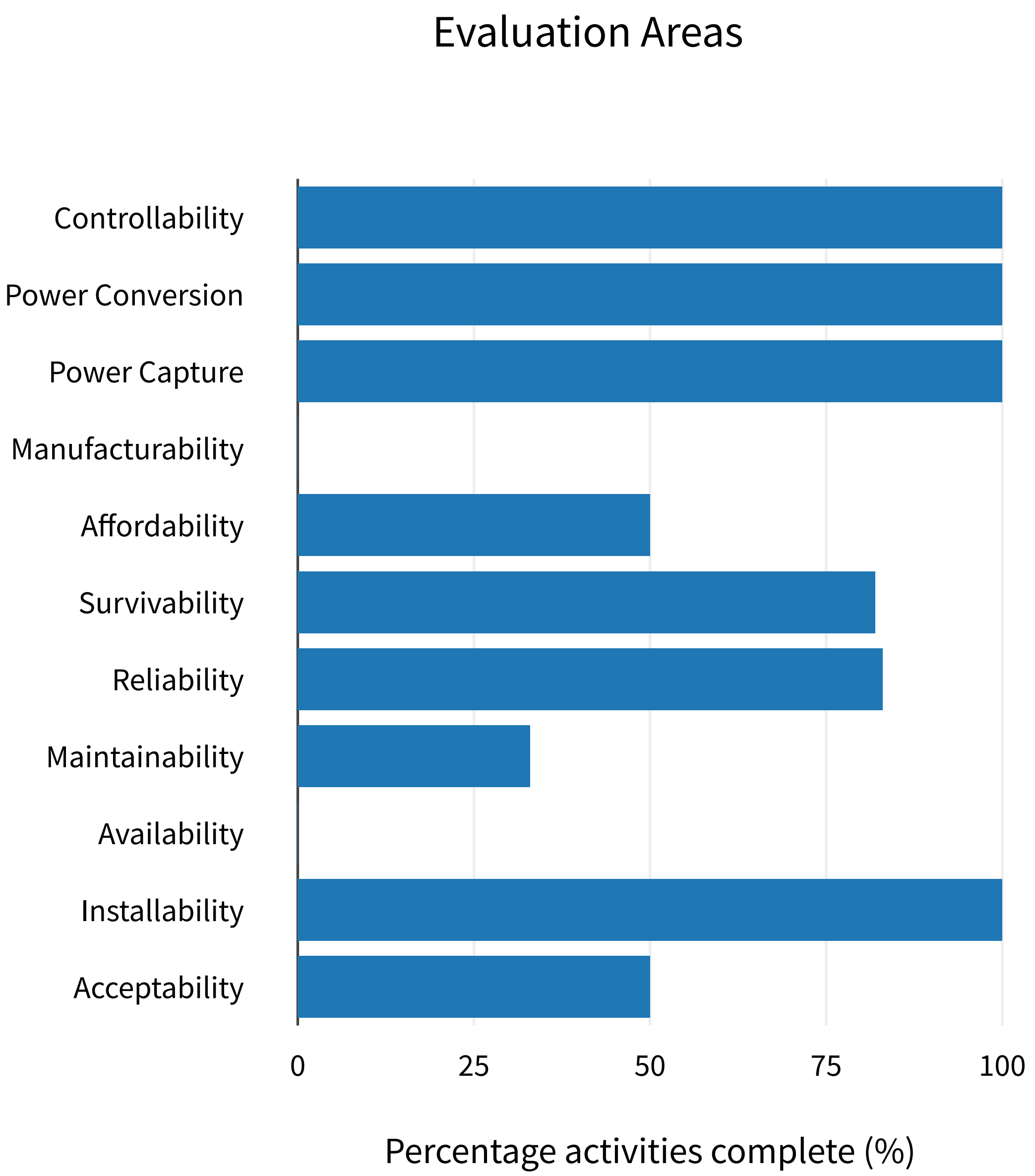
The table below summarises the percentage of activities completed in each of the stages in the Stage Gate framework.

	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
% activities complete	100%	100%	97%	78%	49%	31%

DETAILED RESULTS FOR STAGE 3

Below are two bar- charts summarising the percentage of completed activities for Stage 3, categorised by both activity category and evaluation area.


Activity Categories
Environmental and social impacts
Greenhouse gas emissions
Economic assessment
Testing (open-water)
Testing (tank/open-water)
Testing (rig/tank)
Testing (rig)
O&M
Installation planning
FMEA
Environment characterisation
Structural analysis
Measurement and monitoring
Numerical modelling
0
25
50
75
100
Percentage activities complete (%)


Evaluation Areas
Controllability
Power Conversion
Power Capture
Manufacturability
Affordability
Survivability
Reliability
Maintainability
Availability
Installability
Acceptability
0
25
50
75
100
Percentage activities complete (%)

DTOceanPlus project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785921

Stage Gate Design Tool

Summary report

VALID - UC#3_sg

Stage Gate v1.0.0
30/03/2023

TABLE OF CONTENTS

The following requested sections have been included in this summary report;

INTRODUCTION

This report is an output of the DTOceanPlus Stage Gate design tool. The aim of this report is to assist decision-making through standardised activities, questions and metrics to assess ocean technology development process in objective assessment. For more details on how the Stage DTOceanPlus website or through the Graphical User Interface (GUI) of the software.

STUDY DETAILS

The summary details of the Stage Gate study being assessed are given below:

- Name: VALID - UC#3_sg
- Description: Only Evaluation Areas Assessment
- Threshold settings: Default (no metric thresholds)
- Selected Stage: Stage 3
- Selected Stage Gate: N/A

ACTIVITY CHECKLIST RESULTS

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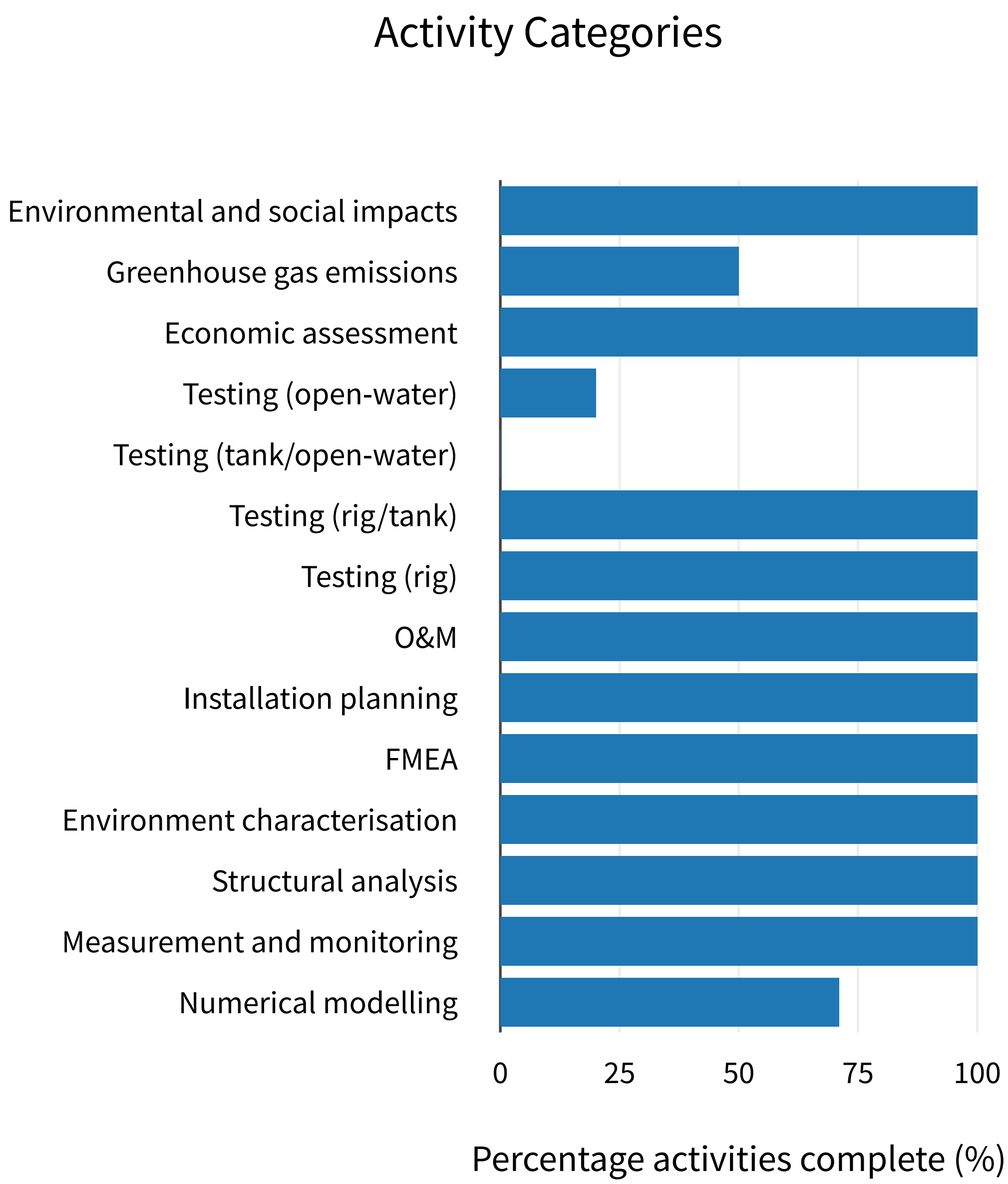
Activity Categories
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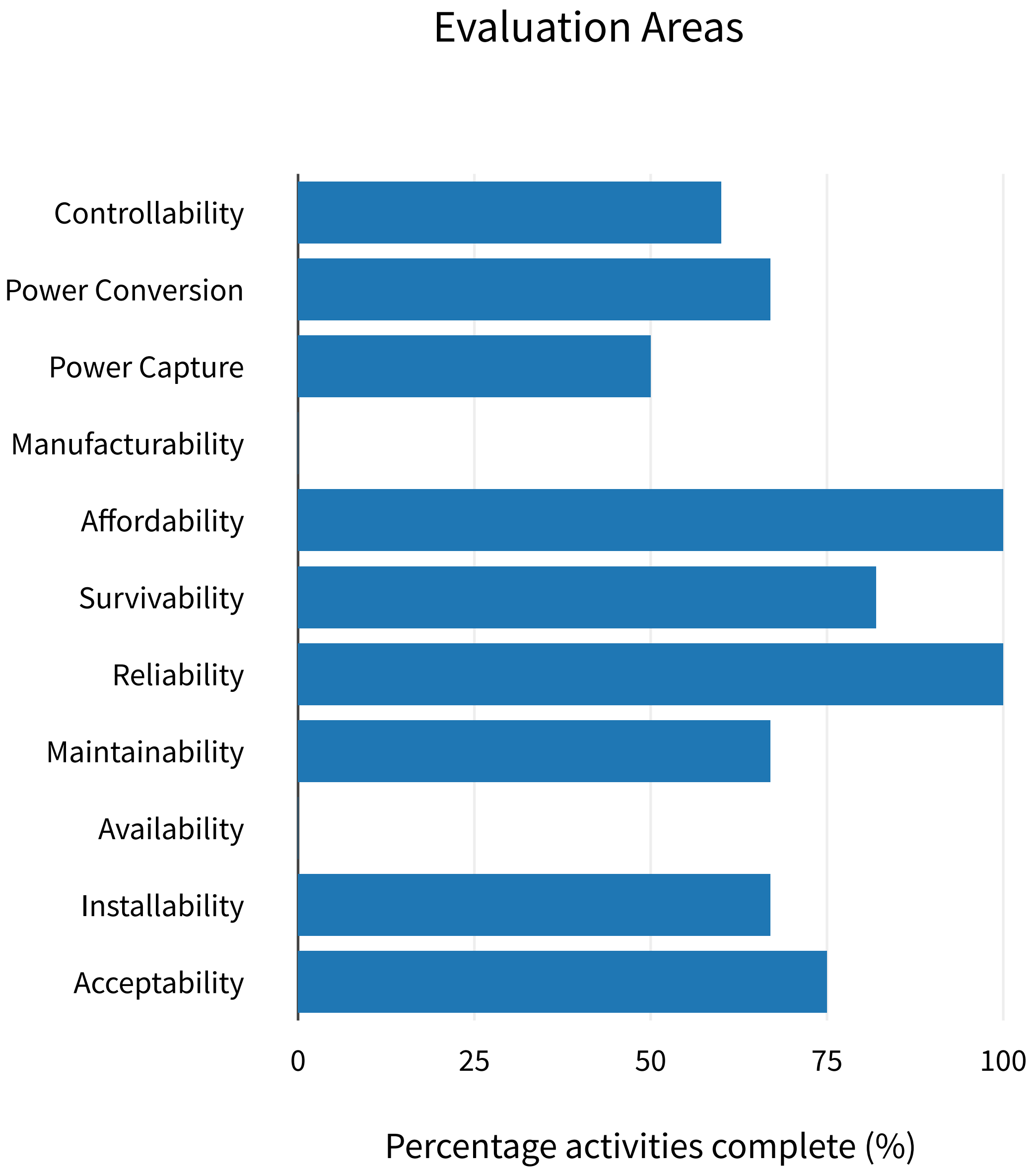
O&M
Installation planning
FMEA
Environment characterisation
Structural analysis
Measurement and monitoring
Numerical modelling
0
25
50
75
100
Percentage activities complete (%)


Evaluation Areas
Controllability
Power Conversion
Power Capture
Manufacturability
Affordability
Survivability
Reliability
Maintainability
Availability
Installability
Acceptability
0
25
50
75
100
Percentage activities complete (%)

DTOceanPlus project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 785921