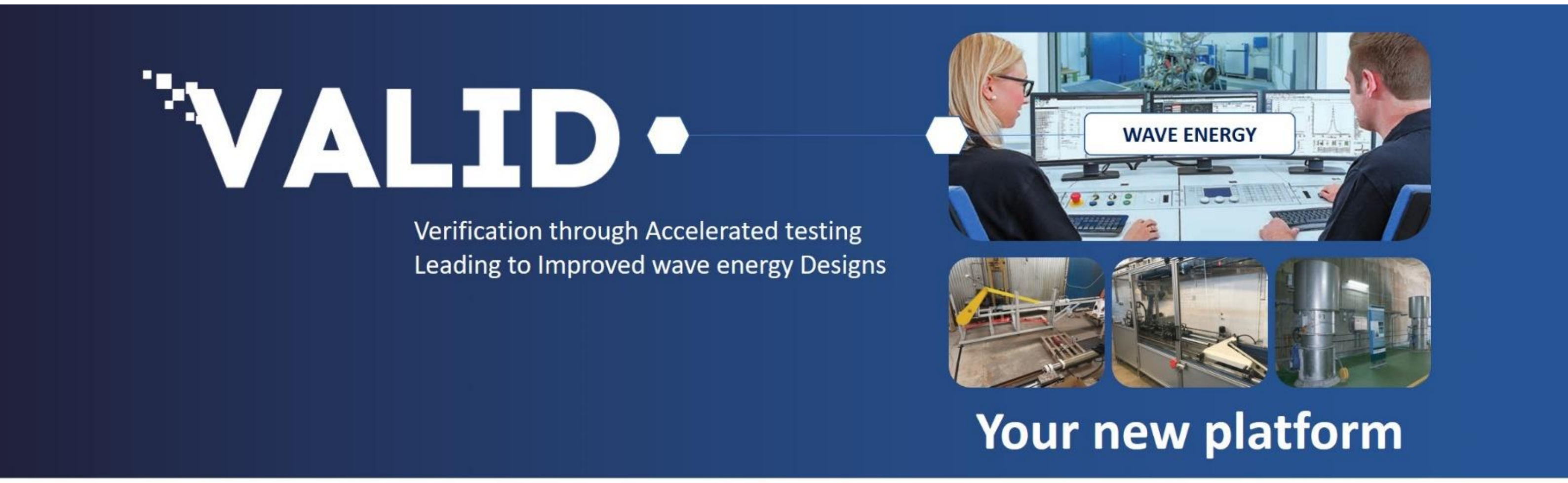
This project has received funding from the European Union's Horizon 2020
research and innovation programme under grant agreement No 101006927.

Verification through Accelerated testing Leading to Improved wave energy Designs



Deliverable 1.1

Accelerated Testing Requirements

Version 1.0

2021-05-31

Lead participant: RINA-C

Dissemination level: Public

DOCUMENT STATUS

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Document History

Version	Description	Approval	Date
1.0	Initial Release	Pierre Ingmarsson (RISE)	2021/05/31

Dissemination level

Short	Type	
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

EU PROJECT NO: 101006927

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Executive Summary

The present report constitutes Deliverable 1.1 *"Accelerated Testing Requirements"*, developed within WP1 of VALID.

The main aim of the report is to give an overview of WEC-System breakdown, the critical components and sub-systems, their related parameters and the associated design requirements for representative ocean energy converters.

Moreover, the report includes a high-level definition of accelerated testing requirements, considering also standards and guidelines for component design and testing for WEC technologies.

Particular attention was given to the case studies detailed in WPs 3 to 5 of the VALID project, for which a preliminary analysis was completed, aiming to identify relevant critical sub-systems and components in the respective WEC designs. The WP leaders provided their relevant FMECA worksheet to RINA, whom subsequently reviewed each of them and summarised the critical sub-systems and components that have been identified.

The report is based on a literature review, input from multiple partners, previous relevant works and data gathered through a customised online survey on the EUSurvey portal. Drawing on these, a ranking of critical components/sub-systems is defined for their assessment in the VALID project.

Project partner names

RISE	RISE Research Institutes of Sweden AB
TECNALIA	Fundacion Tecnalia Research and Innovation
CORPOWER OCEAN	Corpower Ocean AB
RINA-C	RINA Consulting S.p.A.
BiMEP	Biscay Marine Energy Platform SA
IDOM	IDOM Consulting, Engineering, Architecture, S.A.U.
AAU	Aalborg University
AVL	AVL List GMBH
Wavepiston	Wavepiston AS
TU Delft	Delft University of Technology
Aquatera	Aquatera Sustainability Ireland LTD
JFC	Julia F. Chozas, Consulting Engineer
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1 Introduction

This report - Deliverable 1.1 "*Accelerated Testing Requirements*" - is a public document produced in the framework of the VALID project. It relates to work conducted under WP1 "Methodology for accelerated hybrid testing", and more specifically under Task 1.1 "Definition of critical components / sub-systems". In this section, the aim of both the VALID project and this deliverable, the background and a description of the methodology used to identify critical sub-systems and components are sequentially presented in Sections 1.1, 1.2 and 1.3, respectively.

1.1 Aim

1.1.1 VALID Objectives

One of the greatest challenges of our times lies in the climate change issue and the need, expressed by several EU climate and environment targets, to rely on local renewable energy resources. Among these, one of Europe's most promising energy resources lies in our ocean and marine environments, which have the advantage of large areas and high power density. The main renewable energy sources in the marine environment include offshore wind, tidal streams and ocean waves. The latter are one of the largest, if not the largest, unused renewable source in the world, with extremely high energy density, high predictability and low variability, and therefore represent a very promising future energy source, suitable for the decarbonisation of offshore processes and, possibly, desalination purposes, power generation at utility scale etc.. However, Wave Energy Converters (WECs) work in a harsh environment and may be subject to various criticalities and events of failure, which make the exploitation of the technology difficult. WECs are not yet mature enough to overcome the challenges related to cost, performance and reliability in order to realise their full potential, and their development is surrounded by considerable uncertainties.

In order to reduce the probability of failure and design reliable systems, the development of comprehensive design and testing processes is fundamental. In particular, testing offers the possibility to validate and improve confidence in a given design. Failures in components and sub-systems are often detected through extensive and expensive sea trials in the late stages of device development (at higher Technology Readiness Levels, TRLs), which can add significant costs. Comprehensive hybrid testing, mixing both numerical and physical representations of key WEC sub-systems, offers the potential to mitigate such risk and accelerate the development path of a WEC.

The VALID project aims to develop and validate a new test bed platform and procedures for accelerated hybrid testing, which can be used in the wave energy industry to improve the reliability and survivability of components and sub-systems. New testing procedures will be developed, aiming to reduce the development time and cost while enabling a better understanding of the reliability and survivability profiles of critical components, ideally at early TRLs.

1.1.2. Deliverable Objectives

This document aims to identify the critical components and sub-systems of WEC technologies through a desktop research and the interaction with leading industry experts. Related parameters and the associated design requirements have been also identified for representative WECs. Particular attention is given to the user cases of the VALID project – led by CorPower, IDOM and Wavepiston. Based on previous relevant work, practical experience and input from multiple partners, a final ranking of critical components / sub-systems was defined for their assessment in the VALID project, using the Failure Mode, Effects, and Criticality Analysis (FMECA) methodology. Best practices from the design and testing activities with related limitations are also highlighted within the document.

The new test bed platform and methodology will be developed throughout the project in a format suitable for a wide range of WECs, critical components and sub-systems. The identification of the latter within this document therefore represents the starting phase for VALID future activities.

1.2 Background

As stated by the "Directive 2001/77/EC" on the promotion of electricity produced from renewable energy sources in the internal European market, there is a need to diversify and increase the amount of energy obtained from renewable sources. Ocean waves represent a clean and alternative source of power and converting their energy into another useful form of energy has been demonstrated as technically feasible for multiple WEC devices, both of the nearshore and offshore types.

1.2.1 General Description, Strengths and Weaknesses of WECs

A wide variety of WEC technologies with different working principles have been developed to date, depending on e.g. operating principle, orientation and location (see also Section 2).

Wave energy and the use of WECs have different advantages and disadvantages. These are summarised in the Table 1. It is noted that each type of WEC may have its own specific advantages and disadvantages; the consideration of these is outside the scope of this deliverable.

Table 1: Summary of potential advantages and disadvantages of harnessing wave energy

👍	Renewable	Wave energy is a secure source of renewable energy in a changing European energy market, and it is the most concentrated form of renewable energy on earth. Waves are created by the wind and the wind is caused by the irregular heat on the planet's surface driven mainly by the sun which heats different places at different speeds. Since wind will always exist, waves will always be available on the surface of the water to generate electricity, making it a renewable source.[1]
👍	Abundant resource	Wave power fluxes in Europe are often in the region of 30-40 kW/m of wave front – with more than 100 kW/m being available in (deep) offshore regions [1].
👍	Environment Friendly – Small Footprint	Renewable energy sources are the most environmentally friendly and widely available option for power generation. Inherently, wave energy does not emit greenhouse gases when it is generated, like fossil fuels do. A wave power plant occupying less than half a square mile in the ocean would generate more than 30MW of wave power – the equivalent of nearly 20,000 homes.[2]
👍	Easily Predictable and Reliable	Wave energy is more predictable and consistent than wind or solar energy. Sea states can be accurately predicted 48

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[1] https://www.conserve-energy-future.com/advantages_disadvantages_waveenergy.php on 21st April 2021

[2] https://www.linquip.com/blog/wave-energy-advantages-disadvantages/ on 21st April 2021

		to 72 hours in advance, while accurate wind forecasts rarely are available more than 5-7 hours ahead[3]. As a concentrated form of solar energy, wave energy is a more reliable energy source. However, it should be noted that the amount of energy that is carried through the waves varies each year and from season to season. Generally, the waves are more active in winter due to the increase in wind, due to colder temperatures.[4]
👍	Size Advantage	Wave energy devices can be customised to meet the demand for electricity and thus can be produced in different sizes appropriate for each location. Conversely, fossil fuels generally require large plants to produce electricity.
👍	Minimum Visual Impact	Wave energy devices can be installed to be mostly or entirely submerged beneath the water. The devices can be installed far enough from shore to allow for minimal visual impact.
👎	Suitable to Certain Locations	A significant disadvantage of capturing energy from the waves is related to the location of energy demand centres: only those near the ocean will benefit directly. Landlocked nations and cities far from the sea must find alternative energy sources.
👎	Potential Effects on the Marine Ecosystem	As clean as wave energy is, its exploitation may create hazards for the surrounding environment. WECs may disturb the seafloor, change the habitat of e.g. near-shore creatures (like crabs and starfish) and create noise that disturbs the sea life around them. Moreover, building plants or electrical wires directly on the beach might prove challenging because they would be unsightly and can cause damage to marine life and the surrounding ecosystems.
👎	Impact of Maritime Traffic	Power plants that harvest wave energy must be located on the coast and should be close to cities and other populated areas to be of great use to anyone. However, these are places that are the main arteries for e.g. cargo ships, cruise ships, recreational vehicles, etc. Given the large space available at sea, different organisations, such as Marine Spatial Planning, are working hard to establish in which areas WECs can be located were such negative impact is small or even does not exist.
👎	Weak Performance in Rough Weather	The performance of wave power drops significantly during rough weather. WECs must also withstand rough weather (i.e. survive), which can pose considerable design challenges. There is a significant peak-to-mean power ratios in ocean waves, which makes it difficult to efficiently harvest energy while surviving extreme events.

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[3] https://www.waves4power.com/ on 21st April 2021
[4] https://www.solarreviews.com/blog/wave-energy-pros-and-cons on 21st April 2021

👎	Costs of Production	Owing to its infant stage, the costs associated with wave energy technologies are considerably higher than those associated with other renewable energy conversion technologies. There is also considerable uncertainty regarding key cost categories such as e.g. OPEX, given the lack of long testing periods offshore.
👎	Slow Technology Improvements	Wave energy is still at an infant stage, requiring further development to reach technical and commercial maturity. This slow development and the related uncertainty are an obstacle to investment in this type of renewable energy.
👎	Reliability of the technology	The infancy of the technology and the nature of the wave-WEC interaction problem present challenges related to performance, cost and overall reliability. The latter is a key issue that has to be addressed in order to make WEC technologies a viable option for renewable energy conversion.

1.2.2 Mitigation of Design Failures through Accelerated Testing

From Section 1.2.1 it is clear that the development of WECs is surrounded by high uncertainties. In order to realise their full potential, testing is a very valuable activity for both addressing key issues and improving the overall confidence in the design.

To date, most laboratory testing has focused on functional testing (e.g. proof of concept and performance evaluation). At such stages, the assessment of reliability and survivability is somewhat limited. This is demonstrated both in the current TRL definitions for ocean energy [2], where reliability is first assessed at TRL 5 and demonstrated at TRL 6-7; and in the IEC technical standards on recommended procedures for testing pre-prototype devices [3], where fatigue assessment is performed only in phase 3 of field tests.

Furthermore, component testing under realistic conditions (the ocean) is challenging due to the following:

1. It is difficult to reproduce the external environment and its parameters in the laboratory (salinity, humidity, marine growth, etc.).
2. Large-scale testing in dedicated facilities is expensive.
3. The effects of scale bring many uncertainties such as e.g. the inability to model, at component level, a critical sub-system.
4. Monitoring equipment may be difficult to implement.

Therefore, there is a lack of evaluation of the behaviour of future systems in the early stages of technological development (at low TRLs). Sub-system and component failures are often detected only in the later stages of device development through in-depth real-sea testing. Finding a problem with high TRLs can add significant costs and delays to programs and ultimately lead to rebuilding or failure. Performing dedicated tests while still at low TRLs may provide a solution to mitigate possible future problems.

In this context, the VALID project seeks to develop a hybrid testing platform and related methodologies that will support the wave energy industry to accelerate the validation of components and sub-systems early in the development process. Aspects related to accelerated testing are expected to be integral to the VALID procedures (see also Section 1.2.3).

1.2.3 Accelerated Testing

Accelerated testing encompasses a series of test methods for assessing key reliability and survivability metrics such as component life in a reduced amount of time. The aim of such tests is to rapidly obtain data which, when properly modelled and analysed, will yield information on component life or performance under normal use [4].

A crucial part of any test (accelerated or not) is to clearly state its purposes. Usually, accelerated life and performance degradation tests can serve one or more purposes, including the following:

1. Identify, reduce or eliminate failure through better component design.
2. Benchmark existing designs and suppliers.
3. Identify manufacturing defects.
4. Measure sub-system and component reliability.
5. Evaluate design variables that affect reliability.
6. Validate numerical models.
7. Quantify consistency with field data.
8. Develop relationships between reliability (or degradation) and operating conditions.
9. Decide the maintenance schedule (inspect, repair, replace) and spares policy.

Therefore, accelerated testing enables the observation of failure mechanisms and modes which may not be easily observed in short-term field deployments, and can be used to overcome the lack of information by specifically targeting life estimation and defect / design weakness identification.

In such tests, usually the stressors involved are e.g. pressure, temperature, voltage, rates of rotation or duty cycles, loading, and vibration. All these can be scaled up; however, it is more difficult to accelerate the timescale of the effects of the corrosive marine environment upon fatigue, stress corrosion cracking, wear of bearing surfaces, and similar processes. As J. Wolfram summarises: "*simulating the effects of the marine environment is non-trivial but accelerated testing of key common components would be worthwhile*".[5]

For a general overview and background on reliability and accelerated testing, see e.g. [6], [7] and [8].

With emphasis on practical aspects of engineering, [6] has gained worldwide recognition through progressive editions as the essential reliability textbook. It retains the unique balanced mixture of reliability theory and applications, thoroughly updated with the latest industry best practices.

The objective of [7] is to propose a philosophy of engineering test and to describe the necessary technologies and methods that will provide a foundation for all plans, methods and decisions related to testing of engineered products and systems.

[8] supplies a variety of methods for load analysis and also explains their proper use in view of the design process.

Accelerated testing is a well-established approach guided by international standards, which will be analysed in detail in Section 4. Within the VALID project, accelerated testing will be carried out in a laboratory environment with selected physical test rigs (such as those introduced at a high-level in Section 3.3), which allow for controlled testing.

1.3 Methodology for Identification of Critical Sub-System and Components

To achieve a comprehensive and clear idea of the critical sub-systems and components of WECs, different tools have been used in Task 1.1. The information was collected from literature review, from the experience of leading experts in the sector via a survey and from VALID partners (in particular the project user cases). In this way, different points of view were collected to achieve a comprehensive study. From the information gathered, it was possible to carry out a final analysis using the Failure Mode, Effects, and Criticality Analysis (FMECA) methodology for the definition of a ranking of critical components that will be analysed in depth during the VALID project activities.

1.3.1 Literature Review

The first step of the analysis conducted for the drafting of this document was a literature review, through which it was possible to define an overview of the elements that compose a WEC , with its critical components, the current testing and design methodologies and processes, and their best practices, standards and limitations.

Desktop research was mainly based on documents, papers and publications from different significant sources appropriately cited and collected in the Section 3.1 of this document. Further references are made throughout the document, where appropriate.

1.3.2 Surveys

To deepen the overview emerged through the literature review, it was decided to directly contact the wider wave energy community. With this purpose, an online survey composed by 12 questions was launched in the framework of the project (see the survey template in Annex A: Survey).

The online survey was published on the 19th of February 2021 and closed on the 31st of March 2021 via the following link:

https://ec.europa.eu/eusurvey/runner/VALID_WEC_Survey

The survey aimed at gathering information directly from experts from the wave energy community, as a means to gather direct input from those facing the challenges addressed in the VALID project. It investigated stakeholders' perception about standards, guidelines or technical specifications during the design/testing of the WEC critical sub-systems/components [9].

This method was selected since it allows to gather data from a representative sample of the sector. The target groups of the survey were mainly composed by consulting companies, wave technology developers, and research organizations.

RINA-C, as Task1.1 leader and in approval by the WP1 leader and the Coordinator, decided to use the EUSurvey portal, the European Commission's official multilingual online survey management tool compliant with the current GDPR policies (art.13 GDPR 2016/679).

After a first descriptive section where general information was provided on the purpose of the survey, on the VALID project and the privacy policy, the questionnaire was finally divided into three main sections:

- Respondent Profile: to understand from which technical profile the point of view expressed in the survey was received.
- Questions: it represents the core part of the survey through which the information related to the deliverable was collected. The technical questions were single or multiple-choice.
- Conclusions: to leave the possibility to the participant to share any additional opinion through a final open question.

The results of this survey are presented in detail in Section 3.2.

1.3.3 Risk Analysis

In the process of identifying a critical component, it is important to firstly understand under what conditions a component can be defined "critical". As further analysed within the deliverable, according to the *Offshore Safety Directive 2013/30/EU*, a critical element can be defined as a component whose failure may cause or contribute substantially to a major accident. In turn, *major accident* is understood as an event that has important consequences, not only in terms of loss of human life or damage to the environment, but also lack of functionality that leads to the inoperability of the system and consequent significant economic losses. This latter aspect is deeply linked to the concept of reliability [10]: a component is defined "reliable" if it is able to *perform the function for which it was designed under certain conditions and for a specified period of time*.

Having defined such concepts, several ways to identify a critical component and its degree of criticality (FMEA, FMECA, HAZOP, FTA, VMEA) were introduced and addressed in detail - see Section 3.1.3. Using the findings of the literature review and the in-depth study carried out with contributions of industry experts and project partners, the identification of the main criticalities for WECs was completed based on multiple points of view.

Additionally, further interaction with the leaders of the VALID project user cases, CorPower, IDOM and Wavepiston, was conducted – leading to the sharing of the FMEA results developed prior to the start of VALID for the identification of critical components in their design and testing processes. Once all this material had been collected, it was possible to build a final VALID ranking in which the main WEC components and sub-components were listed – see Section 5.

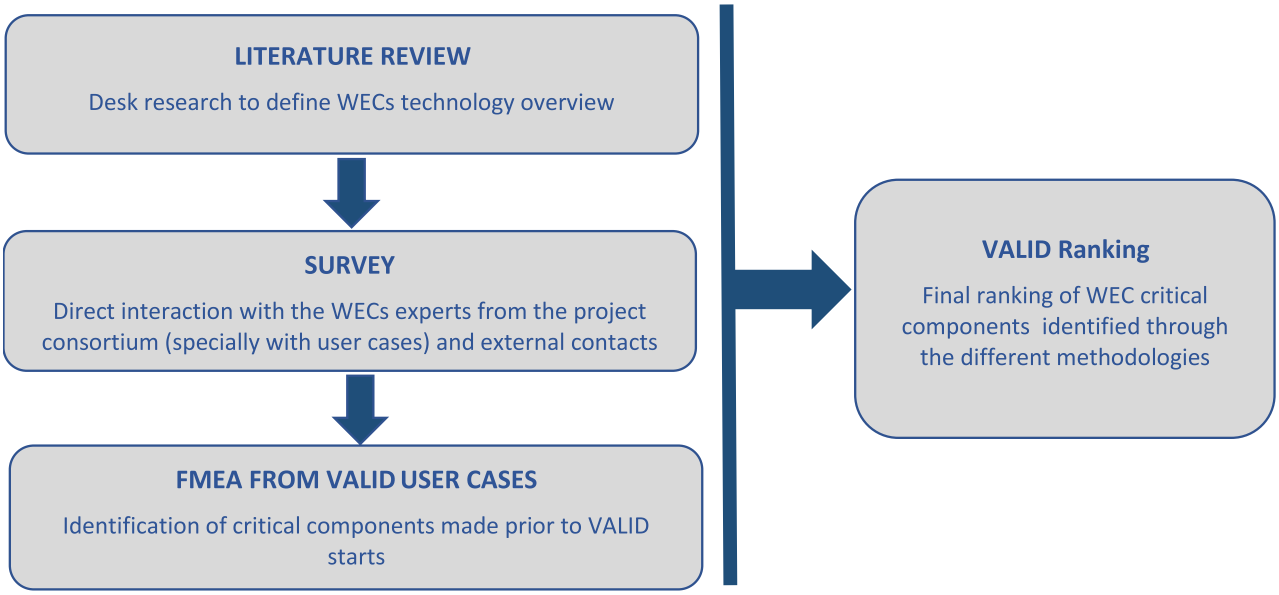

Figure 1: Schematic of the methodology behind VALID's Deliverable 1.1

2 WEC Sub-System Breakdown

2.1 Main WEC Topologies

Although efforts to convert wave energy date back to Girard and sons in 1799 - see e.g. [11], modern wave energy conversion research is often associated with the developments led by Stephen Salter at the Wave Power Group at the University of Edinburgh [12]. Since then, a myriad of wave energy converter concepts has been developed, which introduces a challenge when attempting to define and classify different configurations of WECs.

To address such challenge, numerous WEC classification systems have been proposed, see e.g. [13], [14]. Common alternatives are based on the following criteria:

- Operating principle (oscillating water columns (OWC), oscillating bodies, overtopping).
- Orientation (point absorber, attenuator, terminator).
- Type of Power-Take-Off (PTO) sub-system (e.g. pneumatic, hydraulic, direct-drive).
- Location (onshore, nearshore, offshore).

Several WEC concepts combine multiple characteristics from the different criteria introduced above. Table 2 attempts to summarise the main types of WECs currently under development, based on such criteria[5] and according to EMEC (European Marine Energy Centre)[6]. Although technology development is actively ongoing in the vast majority of these types of WECs and full-scale examples of all the types of WECs introduced in Table 2 have been built, in recent studies - e.g. [15], [16] - point absorbers have been identified as the most common type of WEC currently under development. However, it remains relevant to consider multiple types of WECs as technology convergence has not yet occurred.

Furthermore, from a sub-system breakdown perspective, all types of WECs listed in Table 2 may have the same key sub-systems. From a hybrid testing perspective, such commonality brings the opportunity to address critical sub-systems that are crucial for the development of all types of WECs. An introduction to the most prevalent sub-systems and components, along with their most relevant interactions, is presented in Section 2.2.

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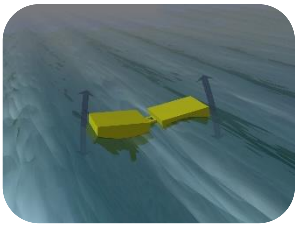
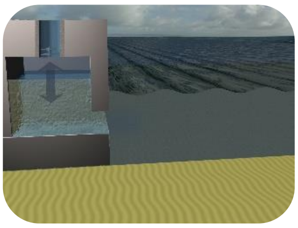
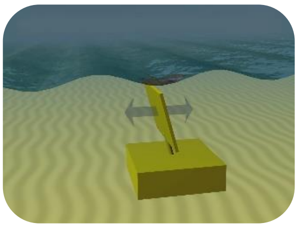
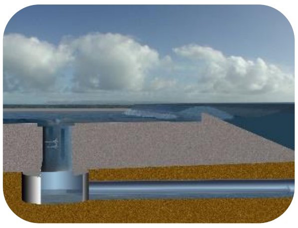
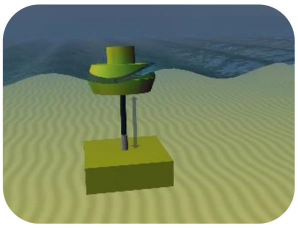
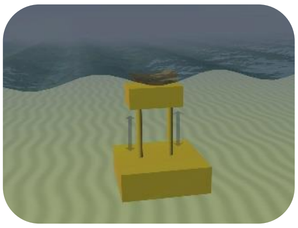
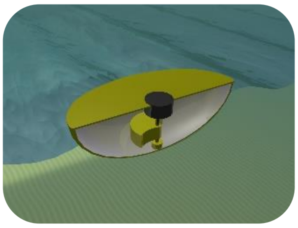
[5] It is noted that Table 2 aims to address the dominant types of WECs, but that additional types of WECs have been proposed to date (e.g. bulge wave; flexible-bag; etc.).

[6] http://www.emec.org.uk/marine-energy/wave-devices/ 21st April 2021

Table 2: Main types of WECs under development (schematics from [17])

WEC type		High-Level Description
	Attenuator	Mainly characterised by its orientation (head-on to the incoming waves). Typically, self-referenced, with more than one floating body.
	Oscillating Water Column (OWC)	OWCs convert the vertical displacement of a column of water into an air flow, which is forced past air turbines to generate power.
	Oscillating Wave Surge Converter (OWSC)	OWSCs convert the horizontal displacement of water particles (surge), typically in nearshore environments. Bottom mounted and floating configurations, bottom and / or top-hinged, have been proposed to date.
	Overtopping	Overtopping devices use the wave run-up over a natural and / or manmade structure to create a head of water. Power is generated via low-head hydraulic turbines as the stored water is released. Bottom mounted and floating designs have been proposed to date.
	Point Absorber	Omnidirectional absorbers of wave energy, typically in heave (translational freedom). Most prevalent for offshore, floating configurations. Wide range of prime mover and PTO solutions proposed.
	Submerged Pressure Differential	Typically, such devices are conceptually similar to point absorber WECs; however, the prime mover is located below the free-surface, thus leading to an energy capture mode based on the pressure change directly above it.
	Rotating Mass	WECs of this type typically convert energy via the relative movement of the outer hull and an eccentric weight (or a gyroscopic arrangement).

2.2 Key Sub-Systems, Components and Relevant Interactions

At a conceptual level, and following e.g. guidance from the Structural Design of Wave Energy Devices project, [18], a WEC may be decomposed in the following key sub-systems (see also Figure 2):

- Hydrodynamic sub-system.
- PTO sub-system.
- Reaction sub-system.
- Power Transmission sub-system.
- Instrumentation and Control sub-system.

Each of the above listed sub-systems holds a key function in the WEC's energy conversion chain. At a high-level, and following Hamedni et al. [18], such key functions can be described as follows: firstly, the *Hydrodynamic* sub-system provides the wave-structure interface that allows the conversion of wave into a form of mechanical energy (or pneumatic energy, in the case of OWCs). The converted energy is then forced to pass via the *PTO* sub-system, while also being resisted by which also interacts with the *Reaction* sub-system, which is the overall responsible for the station-keeping of the WEC in turn interacts with the seabed – leading to both wave-induced forces and, where applicable, wave-induced motions. The *PTO* sub-system also converts the absorbed energy into a useful form of power, such as electricity, allowing the *Power Transmission* sub-system to transport it (in the case of electricity, typically to a power grid). Finally, the *Instrumentation and Control* sub-system uses the data from all relevant sub-systems to derive appropriate command signals, which in turn regulate the WEC response in wide range of design situations (e.g. power production, parked, etc.), effectively defining all key modes of operation.

At a generic level, the above described sub-systems apply to all the types of WECs defined in Table 2. Relevant interactions between the key sub-systems are also detailed in Figure 2.

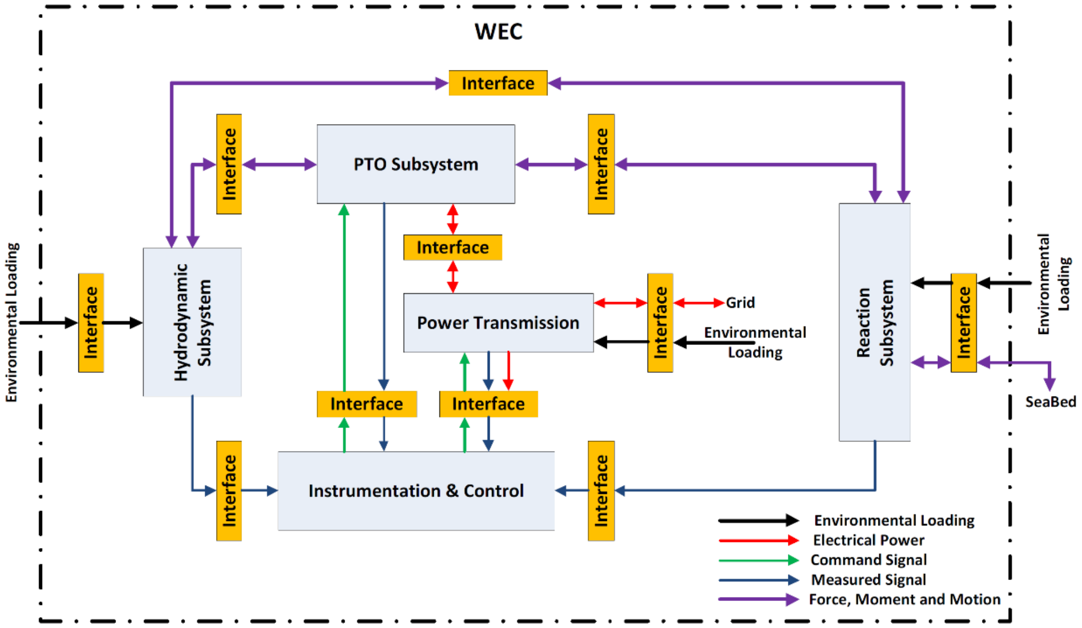


Figure 2: Typical WEC sub-system breakdown [18]

The difficulty of classifying types of WECs based on their sub-systems was also alluded to in [18], mainly due to the diversity of WEC concepts under development. However, the authors noted that with the exception of the *Hydrodynamic* and the *Reaction* sub-systems, all other sub-systems tend to rely on standard, off-the-shelf, components. Such reality offers opportunities in terms of devising methodologies for risk assessment / ranking, as well as accelerated testing practices, that may potentially affect a wide range of WEC technologies – see also Section 6.

As a first step, the PTO sub-system is of particular importance to the VALID project, given that the three proposed user cases – to be explored in WP3, WP4 and WP5 – are dedicated to this sub-system. Furthermore, and following [15], where multiple statistics including WEC related patents and PTO type were analysed, hydraulic PTOs have been identified as the most common choice among technology developers – see Figure 3. Therefore, as an illustrative example, a generic component breakdown of this type of PTO is detailed in this section – to provide a high-level overview of the potential paths to failure that such type of PTO may present. A more comprehensive review of PTO options and of the associated sub-systems for wave energy is available in e.g. [19]; [20]; [21].

The nomenclature and overall principles of the WEC sub-system breakdown illustrated in Figure 2 were also used in the SDWED project to propose a generic WEC risk ranking and the use of standard failure mode analysis methods, along with a high-level risk assessment of WECs. Such findings are further explored in Sections 3 and 5 of this report.

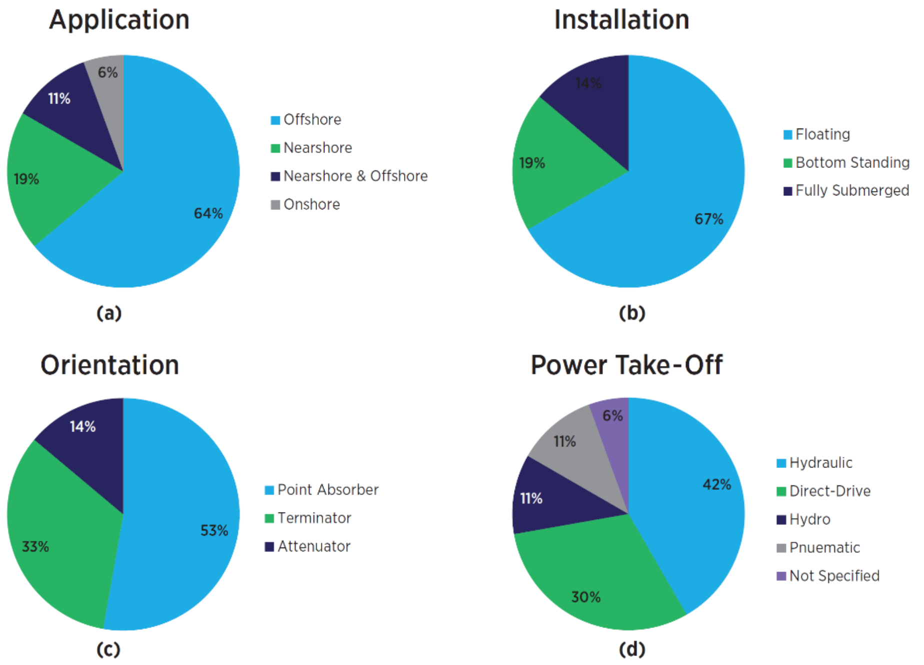


Figure 3: Breakdown of active WEC device including key characteristics [15]

2.2.1 Example: Hydraulic PTO Breakdown

To illustrate the breakdown of a typical WEC PTO system from conceptual to component level, a hydraulic PTO is considered in this section. In such types of PTO, one or more linear actuation(s) system(s) – i.e. hydraulic cylinder(s) – are activated by the wave-induced forces/motions, which can in turn be associated to the hydrodynamic system. The translational motion of the hydraulic cylinder(s) pressurizes hydraulic fluid, which using valves is forced to pass via a circuit leading to a hydraulic motor, which is in turn coupled to an electrical generator. Accumulation capacity is included in the overall system, allowing the decoupling between (instantaneously) absorbed mechanical power and output power, contributing to the creation of a smooth output. In the most typical setup – floating, offshore point absorbers; see also Figure 3 – the PTO is kept onboard the WEC, thus constrained by its overall structural size and geometric characteristics.

A wide range of components may be present in a hydraulic PTO. A generic breakdown is provided in Table 3. It is noted that this is limited to standard hydraulic componentry, i.e. the electrical generation side, to be coupled to the hydraulic PTO, is not listed in Table 3.

Table 3: Typical components of a hydraulic PTO (adapted from [18])

Component	Description
Pumps / cylinders	Convert mechanical into fluid power
Valves	Control / direct the pressure, flow rate and direction of the fluid
Accumulators	Stores the accumulated fluid power
Motors	Convert accumulated fluid power into rotary motion
Fluid	Working fluid in the system (e.g. oil, pressurised water)
Fluid conditioning	Components that affect the working fluid in the system, such as filters and heat exchangers
Fluid connectors	Responsible for connecting different hydraulic components (e.g. hoses, manifolds)

Notorious examples of different types of WECs that have used a hydraulic PTO and reached full-scale status include the Pelamis (e.g. [17]) and WaveRoller WECs (e.g. [22]). For the former, Figure 4 illustrates both the components and their layout in a Pelamis power module – which in the original Pelamis WEC concept connected the main tubes and was rated at 250kW, with three power modules per WEC (leading to an installed capacity of 750kW).

Finally, relevant interactions of a generic hydraulic PTO sub-system are illustrated in Figure 5, to highlight the coupling and potential failure paths that it may be subject to. The connection to auxiliary sub-systems, responsible for support functions that affect the overall WEC response, and in turn the PTO response itself, is also highlighted in Figure 5 - see also Section 2.2.2.

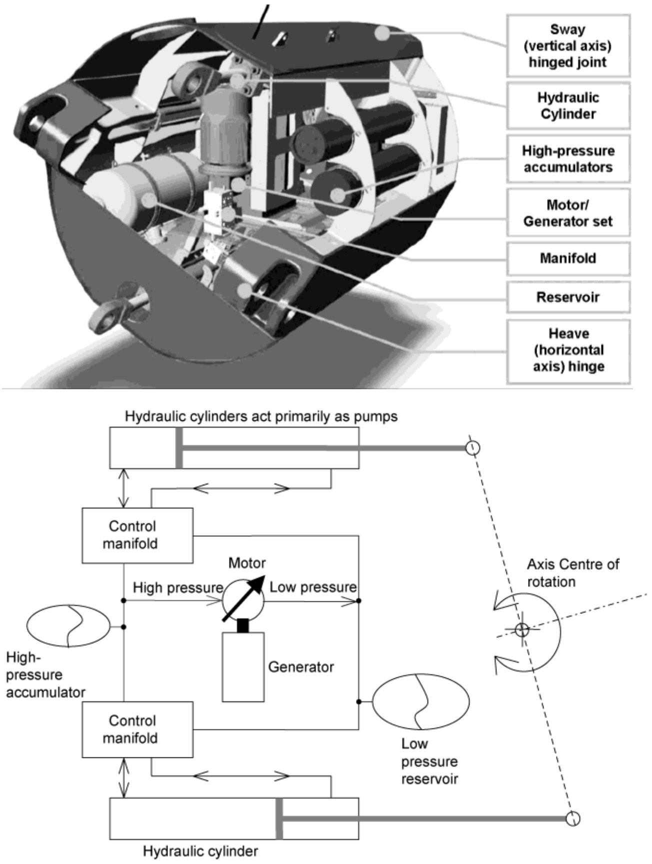


Figure 4: Overview of a Pelamis power module (top) and schematic of the hydraulic PTO [23]; [17]

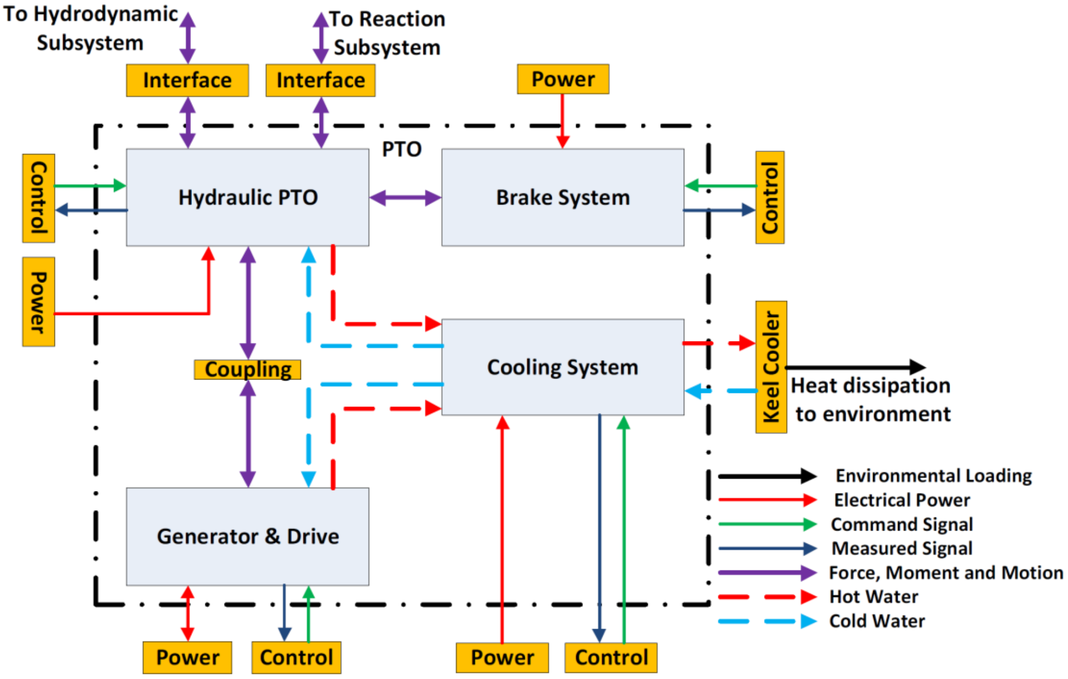


Figure 5: Schematic of the interactions of the PTO sub-system [18]

2.2.2 Auxiliary Sub-Systems

As illustrated in Figure 5, the normal operation of the PTO is dependent on a range of auxiliary sub-systems. These sub-systems vary from WEC to WEC, but in general are included in the WEC to ensure that the normal mode of operation can be achieved and kept, at safe and reliable levels.

In the WEC breakdown originally proposed in [18] and followed in this section, such auxiliary systems can be considered as part of the PTO sub-system. It should be emphasised that the presence of any particular auxiliary sub-sub-system is intrinsically linked to the main key sub-system and the type of WEC.

Some typical examples include:

- Brake/Latch System.
- Shock Absorption System (e.g. end-stops).
- Heating/Cooling System.
- Lubrication System.
- Sealing System.
- Ballasting System.
- Fire Fighting System.
- Backup Power System (e.g. batteries, diesel generators).

The critical assessment of the effects and interactions of auxiliary systems in the overall WEC and sub-system response is therefore essential, to ensure that all relevant failure modes are considered and that appropriate mitigation measures are devised, where appropriate. Furthermore, and where applicable, experience from other industries may be sought, noting that the consideration of the specificities of wave energy conversion in terms of e.g. peak to root-mean-square (RMS) load ratios, relevant design load cases (DLCs), etc. is also essential.

To conclude, it should be noted that although Section 2.2 addresses the identification of the main sub-systems that may feature in a typical WEC, focusing on a hydraulic PTO as a representative example, it does not make any inferences on how the criticality of any given sub-system(s) and / or component(s) may be deduced. Such topic is addressed in Section 3, where methodologies for the identification of critical of sub-systems and components are discussed, with particular attention given to WEC related and user case specific aspects.

3 Identification of Critical Sub-Systems and Components

3.1 Literature Review of WEC Specific Work

3.1.1 Introduction

As noted in Section 1.3, the main aim of this document is to identify the most critical sub-systems and components of a WEC. As a starting point, a literature review based on documents, papers and publications was conducted. The results of such review are presented in the following sub-sections.

3.1.2 Critical Components: Reliability and Survivability

Following the definitions introduced in Section 1.3.3, a critical element can be defined as a component whose failure may cause or contribute substantially to a major accident. The identification of the potentially critical sub-systems and components is rooted in the economic impact that downtimes and failure may have. Such impact may be more relevant for devices like WECs, which operate unmanned and in the ocean environment, with the consequence of potential difficulties for maintenance operations that could extend the downtime of the device.

WECs have great potential as renewable energy conversion technologies. However, the successful implementation of WECs technology depends largely on their reliability and survivability [10], which is yet to be proven at large scale. A possible definition of both reliability and survivability, following e.g. [10], can be given by:

- *Reliability* is defined as the ability of an item to perform a necessary function under given conditions for a given time interval.
- *Survivability* is a measure of the ability of a sub-system 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.

Further discussion and potential theoretical methods to assess reliability and survivability related metrics shall form part of the VALID's Deliverable 1.2 "*Critical Components and Modelling Limitations*".

3.1.3 Risk Analysis Methodologies for the Identification of Critical Components

In order to identify all the possible failure modes of a WEC and the associated relevant mechanisms, a risk analysis should be carried out in the design phase. There are different risk analysis methods commonly in use to identify potential criticalities. A shortlist of typical methods primarily used in industry is provided below - see also e.g. [18]. These methods are analysed sequentially in the following sub-sections. Further considerations into other types of methods (e.g. probabilistic based methods) are also made in VALID's Deliverable 1.2, and will complement this review.

- Failure Mode & Effect Analysis (FMEA).
- Failure Mode, Effect and Criticality Analysis (FMECA).
- Hazard Identification Study (HAZID).
- Hazard and Operability study (HAZOP).
- Fault Tree Analysis (FTA).
- Event Tree Analysis (ETA).

- Structured What-if checklist (SWIFT).
- Variation Mode and Effect Analysis (VMEA).

3.1.3.1 FMEA/FMECA

A FMEA/ FMECA is a semi-quantitative procedure for analysis of potential failure modes, with a system for classification by frequency of occurrence against the severity of their consequences (determination of the effect of failures on Production, Assets, Safety, and Environment), and the detectability of the failure itself.

It provides detailed insight into the systems' interrelationships and potential paths of failure, and consists in a systematic analysis of the Design Documentation as Block Flow Diagrams (BFD), Process Flow Diagrams (PFD), Piping and Instrumentation Diagrams (P&ID), Wiring Diagrams, Process Description, etc.

Failure modes Risk Ranking is allowed by means of the Criticality Index (CI). The analysis enables to focus on the highest risks threatening plant efficiency and safety, allowing remedial effort to be directed where it will produce the greatest value.

Input Documentation

For the development of the FMECA the following documentation is generally required (where applicable):

- Process Flow Diagrams (PFD).
- Piping & Instrumentation Diagrams (P&ID).
- Block Functionality Diagram (BFD), if available.
- Process System Description.
- Mechanical Layouts.
- Wiring Diagrams
- Hydraulic schemes.
- Instrument Air Diagrams.
- Emergency Shut Down Diagram.

Methodology

The system subject to the analysis is subdivided into components at the desired level depending on the information available for the analysis (e.g. sub-system, component, sub-component). The analysis focuses on all Reference Items (RI) composing the system under analysis and identifies the possible failure modes of each item and evaluates the consequences of such failure. The approach is based on a "single failure" criterion, i.e. it assesses each failure considering the other equipment functioning in normal condition.

A FMECA worksheet is developed for each Process and Utility Unit. The following main items are identified and recorded in such worksheet:

- Unit: Reference Plant Unit for each item.
- Item tag and description: Reference tag and functional description of each item.
- Failure modes and causes: Most predictable failure modes and the relevant causes for each item.

- Likelihood: Evaluation of the likelihood of each failure mode (frequency of occurrence) on the basis of engineering experience of the relevant experts of the working team and/or international databases. Likelihood can be defined as per the notes in Table 4.
- Local failure effect: Qualitative considerations about effects of each failure mode on the surrounding installation(s).
- Global failure effect: Qualitative considerations about consequences/effects of each failure mode on the plant production are recorded and their severity is evaluated in terms of impact on Safety, Environmental protection, Assets and economic loss due to installation unavailability (see Table 5). The screening is semi-quantitative and can be based on the Risk Matrix approach (see Table 6 and Table 7).

Table 4: Likelihood classes (adapted from e.g. [24])

Class	Name	Description	Indicative Annual Failure Rate	Reference
1	Very Low	Negligible event frequency	$1x10^{-4}$	Accidental
2	Low	Event unlikely to occur	$1x10^{-3}$	Strength / ULS
3	Medium	Event rarely expected to occur	$1x10^{-2}$	Fatigue / FLS
4	High	One or several events expected to occur in lifetime	$1x10^{-1}$	Operation low frequency
5	Very High	One or several events expected to occur each year	1	Operation high frequency

It has to be highlighted that in Table 4: Likelihood classes (adapted from e.g. [24]) are reported the likelihood classes generally used in the FMECA methodology for generic industrial devices. In the specific, Class 1 and 2 are difficult to apply to a WEC with a lifetime around 20-25 years.

Table 5: Consequences classes (adapted from e.g. [24])

Class	Description of consequences - Device Level				
	Safety	Environment	Operation	Assets	Economic loss [€]
1	Negligible injury, effect on health	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1k
2	Minor injuries, health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	10k
3	Moderate injuries and/or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	100k

4	Significant injuries	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of production up to 1 month	Significant but repairable outside maintenance interval	1M
5	A fatality	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 1 month	Loss of device, major repair needed by removal of device and exchange of major components	10M

- Detection Method: Considerations about detection methods of each failure (e.g. visual or Audible warning devices, Continuous/Periodic condition monitoring, Inspection, Casual observation, Periodic preventive maintenance, Functional testing etc.) foreseen in the engineering design.
- Compensating Provisions: Information about safeguards (e.g. operating procedures, hardware equipment, stand-by items, buffer systems, etc.) and existing barriers (i.e. instrumented functions) – foreseen in the engineering design – to eliminate or mitigate the effects of each failure.
- Criticality Index: criticality indexes are determined separately for each category of consequence, following the matrix reported hereafter**.** Risk matrix can be defined by putting the probability of failure in y axis and the consequences in x axis. In the matrix below, the risk considered "high" is the risk with overall score equal or bigger to 15.
- The risk level is determined as reported in Table 7.

Table 6: Risk categories (adapted from e.g. [18])

	Consequences				
Likelihood	1	2	3	4	5
5	5-Low	10-Medium	15-High	20-High	25-High
4	4-Low	8-Medium	12-Medium	16-High	20-High
3	3-Low	6-Low	9-Medium	12-Medium	15-High
2	2-Low	4-Low	6-Low	8-Medium	10-Medium
1	1-Low	2-Low	3-Low	4-Low	Medium

Table 7: Risk matrix

Risk Matrix	Low	Tolerable, no action required
	Medium	Mitigation and improvement required to reduce risk at low
	High	Not acceptable: mitigation and improvement required to reduce risk to Low (ALARP)

3.1.3.2 HAZID

HAZID (Hazard Identification Study) is a structured review technique for the early identification of all significant hazards associated with the particular activity under consideration. The scope of the HAZID study is to review the project main choices in order to:

- Identify any hazards which may pose a risk to personnel, to the general public, to the equipment or to the environment due to the normal operation conditions.
- Estimate qualitatively the magnitude of the risk associated to the identified hazards.
- Check whether the precautions proposed for the design/construction activities are sufficient to mitigate the risk to an acceptable level, or provide recommendations for the further risk reduction, if required.

The overall intent of an HAZID study is to demonstrate that the risks associated with all the identified hazards are managed and will be reduced to an acceptable level by:

- Checking the design and considering whether any external or internal cause may generate a hazard to people working on the installation and/or to the general public, and/or a damage to the assets and/or impacts to environment or on company reputation.
- Checking whether the precautions and safeguards incorporated in the project are sufficient to either prevent the hazard occurring or mitigate the severity of any consequence to an acceptable level.
- Identifying and implementing additional precautions or safeguards to manage all the hazards not sufficiently incorporated during the design phase.

The HAZID study is carried out by a multi-disciplinary team comprising a facilitator, project discipline engineers and company's representatives, if necessary. The team will have the duty to recommend modifications or additional studies, as necessary.

3.1.3.3 HAZOP

The HAZOP (Hazard and Operability) technique consists in a systematic analysis of the design in order to assess any operability problems or process-related hazards. This is developed by reviewing each P&ID using a structured step by step approach that allows to comprehensively analyse the whole process via suitable guide-words, used to identify possible deviations from the intended operations. [25]

A summary flow chart of the HAZOP process is shown in Figure 6.

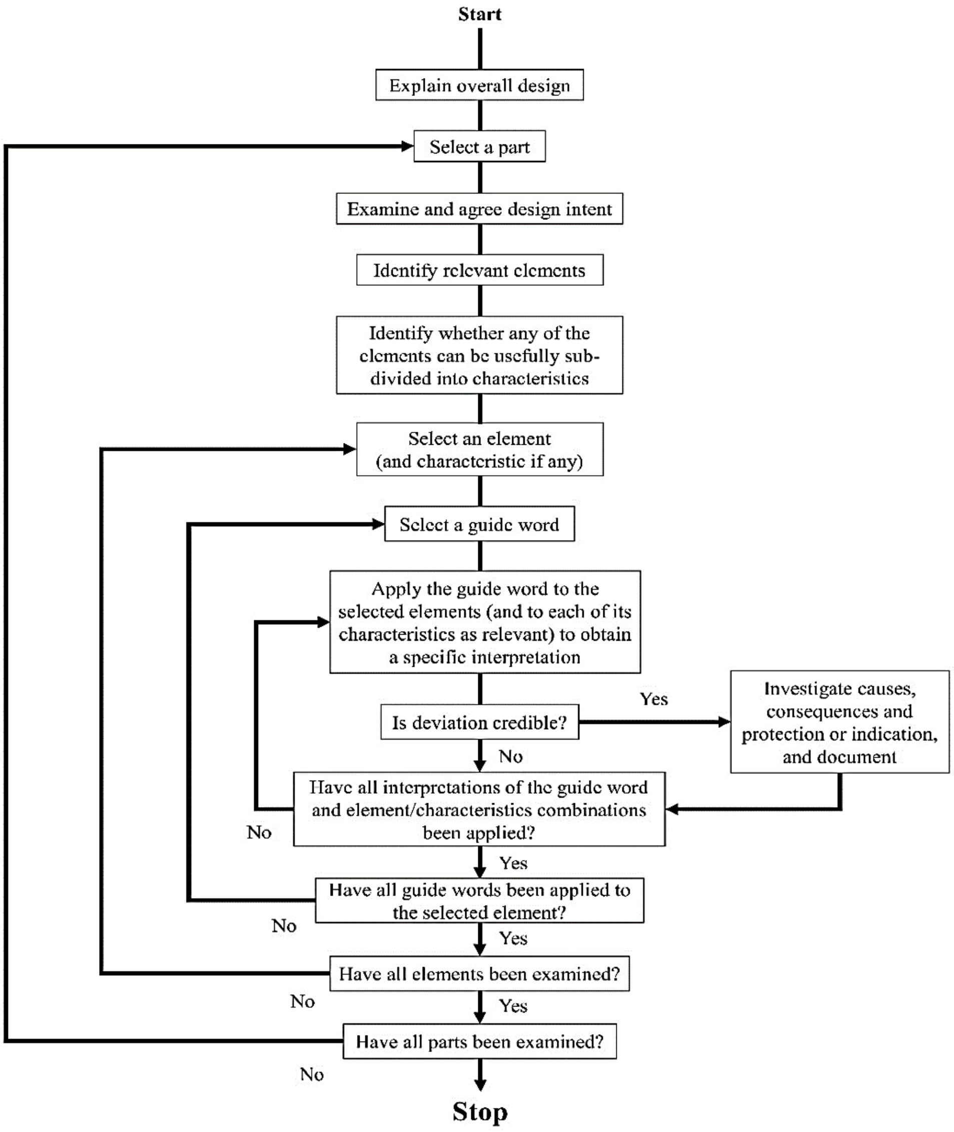


Figure 6: HAZOP flowchart [26]

The first step of the analysis consists in the identification of the "nodes". A node is a system, sub-system or component which can be analysed by itself, together with the relevant connections to the interfaces. The totality of the nodes shall cover all the systems under analysis, without missing any portion of them, until the whole process/scope of work is analysed (identical items can be analysed as "typical", addressing only one of them).

Each node is reviewed by examining which deviations from normal operation can lead to undesired outcomes. All applicable deviations are examined combining appropriate guidewords to the relevant process parameters.

For each deviation, the review team identifies the possible cause(s), its consequences (qualitatively) on process and operation and verifies the existence of sufficient systems of prevention, detection and correction/mitigation of the outcomes.

3.1.3.4 Fault Tree Analysis (FTA)

As described in e.g. [27], Fault Tree Analysis (FTA) is an analytical technique wherewith a critical state of a system is specified. Such system is then analysed in its working context (in terms of environment and operation) in order to find all the possible modes in which the undesired event can happen.

The different parallel and subsequent combinations of faults that will occur in the undesired event are graphically represented in the fault tree model. Events like hardware failures, human errors, or any other related events leading to failure can be defined as faults.

Failure is the top event of the fault tree, which identifies the correlation between basic events which lead to failure.

A fault tree includes the most credible faults as identified by the analyst, this means that it's not necessary that it includes all the potential failures of a system or its all possible failure modes.

The top event constitutes the particular failure mode of the system to which a fault tree is tailored. Therefore, it includes only those failures related to this top event.

Furthermore, FTA is a qualitative model that can be evaluated quantitatively and not a quantitative one.

"Gates" constitute the set of entities of which a fault tree is made, and they allow or forbid the passage of fault logic up the tree. The gates show the relationships between events necessary for a "higher" event to occur. The output of the gate is called "higher" event while the "lower" ones are input to it.

An example schematic of a FTA diagram is illustrated in Figure 7.

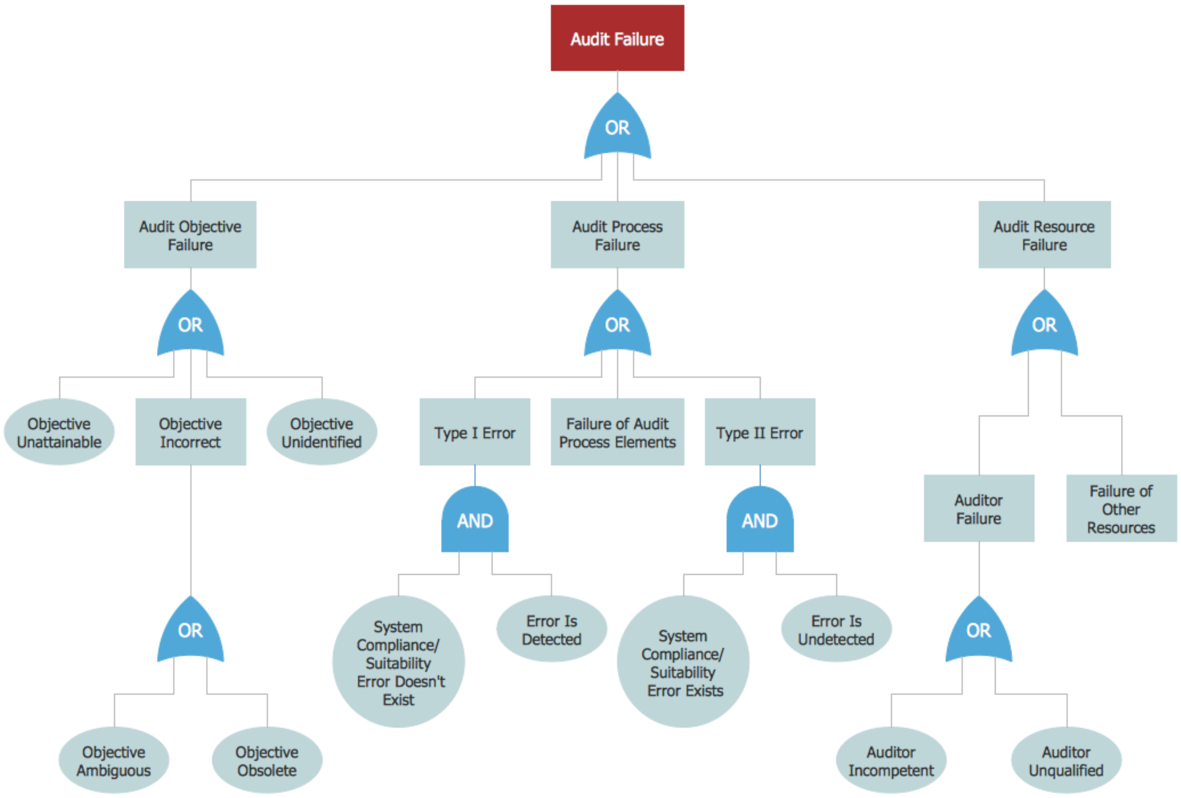


Figure 7: Example of FTA[7]

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[7] https://www.conceptdraw.com/samples/engineering-FTA on 7th May 2021

3.1.3.5 Event Tree Analysis (ETA)

According to [28], an Event Tree Analysis (ETA) is an inductive procedure that shows all possible outcomes resulting from an accidental event, taking into account whether installed safety barriers are functioning or not. Such barriers are the method that most well-designed systems have in order to stop or reduce the consequences of potential accidental events. By studying all relevant accidental events (that have been identified by a preliminary hazard analysis e.g. HAZOP), the ETA can be used to identify all potential accident scenarios and sequences in a complex system. Design and procedural weaknesses can be identified, and probabilities of the various outcomes from an accidental event can be determined.

A general example of ETA is illustrated in Figure 8.

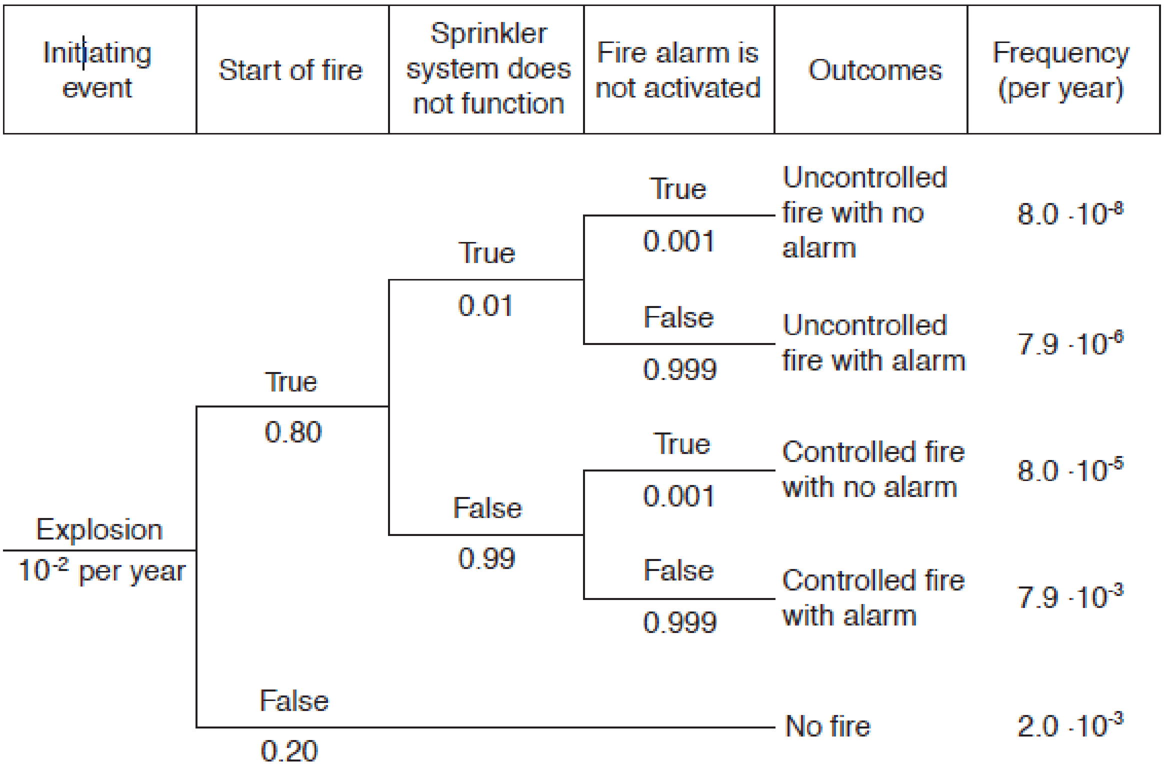


Figure 8: Example of ETA [28]

The main steps of a typical ETA are reported here below [28]:

a. Identify and define a relevant accidental event that may give rise to unwanted consequences.
b. Identify the barriers that are designed to deal with the accidental event.
c. Construct the Event Tree.
d. Describe the potential resulting accident sequences.
e. Determine the frequency of the accidental event and the conditional probabilities of the branches in the event tree [29].
f. Calculate the probabilities/frequencies for the identified consequences.
g. Compile and present the results from the analysis.

3.1.3.6 SWIFT

The Structured What-If Technique (SWIFT), as reported in [29] is a system-based risk identification technique that employs structured brainstorming, using pre-developed guidewords in combination with prompts elicited from participants (which often begin with the phrases "What if…" or "How could…"), to examine risks and hazards at a systems, sub-systems or components level.

Analysing high-level processes, the SWIFT can often be conducted more quickly than more detail-oriented methods and time saving is a significant advantage. The corresponding disadvantage is that some hazards may be disregarded using the SWIFT approach that would be highlighted using more detail-oriented methods like HAZOP or FMEA.

SWIFT does not need to be used on a standalone basis, however, it can be used as the first part of a staged approach to quickly identify processes and sub-systems for which it would be worth the investment of conducting a FMEA, HAZOP, FTA or other detail-oriented risk assessment. While the outputs of a SWIFT are qualitative, the technique can be used to identify sub-systems/processes that could benefit from a quantitative approach.

Considering that the SWIFT methodology foresees that the potential risks are elicited from participants, it is important to assemble an experienced team when using this approach; ideally this should include the representation of all stakeholder groups and those with the most intimate knowledge of the system or process being assessed.

The procedure for a Risk Assessment Using SWIFT is reported here below (adopted from [29]):

1. Prepare the guidewords (selection of a set of guidewords to be used in the SWIFT).
2. Assemble an experienced and skilled team.
3. Describe the trigger for the SWIFT.
4. Articulate the purpose of the SWIFT.
5. Define the requirements (in terms of criteria for success).
6. Describe the system.
7. Identify the risks/hazards (this is where the Structured What-If Technique is applied. Use the guidewords / headings to each system, high-level sub-system or process step in turn. Participants should use prompts starting with the phrases like "What if…" or "How could…" to elicit potential risks / hazards associated with the guideword).
8. Assess the risk (using either a generic approach or a supporting risk analysis technique, estimate the risk associated with the identified hazards).
9. Propose actions (propose risk control action plans to reduce the identified risks to an acceptable level).
10. Review the process (determine whether the SWIFT met its objectives or whether a more detailed risk assessment is required for some components) [30].
11. Overview (production of a brief document with the results of the SWIFT).
12. Additional risk assessment (if required, conduct more detailed risk assessment).

3.1.3.7 VMEA

As reported in (Jonas Pavasson, 2011), the Variation Mode and Effect Analysis method (VMEA) is a statistically based method used to analyse the effect of different sources of variation on a specific process or product.

VMEA is used to recognize and measure the origin of the variation and the manner they impact the system and its relevant characteristics, in order to be able to increase the reliability of the system.

VMEA is a deductive method that can be divided into three different levels:

- Basic VMEA is used in the early design stages, where information about the variation is unclear and the scope is to compare and evaluate different concepts.
- Enhanced VMEA is used later in the design stages, where more information about the source of variation is known.
- Probabilistic VMEA is used in late design stages, where detailed and statistical information about sources of variation is available [31].

In general, VMEA and FMEA are similar methods, the main difference between them is that VMEA is founded on the variation, while FMEA is built on failure concept. Basic and enhanced VMEA are analogous to FMEA in the personal origin of a Variation Risk Assessment and Prioritization number. In the probabilistic VMEA, instead, it is possible to examine with a larger objectivity how each variation can influence, for example, the safety factors.

3.1.3.8 Summary of Risk Analysis Methodologies for Identification of Critical Components

Several methodologies for the identification of critical systems, sub-systems or components have been presented in the previous sections. A list of potential advantages and disadvantages of each method is reported in the table below.

Table 8: Potential advantages and disadvantages with different threat assessment methods (adapted from [31]).

Method	Advantages	Challenges/Disadvantages
FMEA/FMECA	Systematic and simple to apply.	Investigating ONE failure mode at a time may not identify critical combinations of failures.
HAZID/HAZOP	Systematic method which enables identification of the hazard potential of operation outside the design intention or malfunction of individual items.	Resource consuming. Requires detailed information for producing useful results. Experienced facilitator required.
FTA/ETA	Thorough investigation of (already) identified incident.	Not applicable for identifying (new) incidents. Time consuming to set up. Not suitable for accurately modelling all types of systems.
SWIFT	Applicable even if detailed design information is not available.	Experienced facilitator essential, as well as good checklists.
VMEA	Basic and enhanced VMEA require fewer input data. Probabilistic VMEA quantitatively analyses how each included variation contribution affects factors.	Basic and enhanced VMEA have a lower level of accuracy. Probabilistic VMEA needs a lot of data.

FMECA and FMEA are the methodologies selected from the User Cases to identify their critical components. Their analysis will be studied in detail in Chapter 5.

3.1.4 Identified Criticalities from the Literature Review

The aim of the methodologies listed in the section above is to identify all the possible criticalities, failure modes and related mechanisms of a product or process. Failure modes refer to how a device can fail, while a failure mechanism is the material faults that cause the failure. In general, a failure mode is the direct effect of a failure mechanism. Below are listed all the results obtained from the literature review of the WEC technologies.

3.1.4.1 Most Common Failure Mode and Mechanisms for Wave Energy Converters

Table 9 reports common failure modes for a WEC, see e.g. [32]

Table 9: Common failure nodes of a WEC (adapted from [32])

Moorings	Structural	Hydraulic	Electrical	Instrumentation
Loss of pretension	Loss of watertight integrity	Seal failure	Electrical short	Calibration error
Entanglement	Hull breach	Hose burst	Connector fault	False alarm
Drags from position	Structural failure	Water ingress	Generator failure	Software fault
Structural failure	Deformation / yielding	Oil leakage	Electrical overload	Intermittent output
Incorrect orientation	Disconnection	Valve jams shut/open	Battery failure	Communications failure

The consequence of each of the above-mentioned failure modes is an impossibility of the device to perform its normal activity (in this case, to capture wave energy and convert it into electricity). A list of root causes of failure (failure mechanisms) is reported in the table below. Such causes, according to [32], are taken from a FMEA carried out on an offshore wind turbine [33] and converted for a WEC device.

Table 10: Common failure mechanisms of a WEC (adapted from [32])

Mechanical	Electrical	Structural	Marine Environment	Hydraulic
Corrosion	Calibration error	Design fault	Entanglement - moorings	Contamination - Debris
Fatigue Limit State (FLS)	Connector failure	Service loads	Biofouling (airborne)	Contamination - Moisture
Ultimate Limit State (ULS)	Electrical short	Poor installation	Marine growth (subsea)	Contamination - Air
Accident Limit State (ALS)	Insulation failure	Maintenance fault	Ship impacts	Overpressure
Insufficient lubrication	Lightning strike	Manufacturing defect	Foreign body impacts	Miscibility – poor mixing
Overheating	Loss of power			Choked – excessive flow
Bolt loosening	Conducting debris			
Malicious damage	Software design fault			

Mechanical	Electrical	Structural	Marine Environment	Hydraulic
Vibration fatigue				
Material degradation				

3.1.4.2 Examples of Reliability and Survivability Issues in WECs

Some examples of potential reliability issues presented in [34] are directly reported in the following sections (3.1.4.2.1 to 3.1.4.2.4).

The WEC technologies and sub-systems examined are listed below:

- Oscillating Water Columns (OWC) with air turbines;
- Point Absorber (Direct Drive Linear Generator);
- Hydraulic PTO System;
- Overtopping (with Water Turbine as PTO).

3.1.4.2.1 Oscillating Water Column

Three examples of OWC devices that have been developed at full-scale are LIMPET, Pico and Oceanlinx device.

1) *LIMPET device*, decommissioned in 2012 after 12 years of operation, is shown in Figure 9.

Figure 9: LIMPET WEC device

Despite a weekly maintenance regime and habitual maintenance operation was scheduled for the LIMPET (Land Installed Marine Power Energy Transmitter) device, the following issues took place in the first couple of years of operation, as stated in [34]:

- Blockage of collector;
- Vibration loosening of bolts and screws;

- Vane valve flutter;
- Seizure of the butterfly valve shaft bearings;
- Storm damage with water ingress.

2) The Pico Plant OWC (see Figure 10) was put into operation in 1999 and was renovated between 2004 and 2006. In particular, a complete replacement of the electrical equipment and the restoration of some mechanical components were carried out.

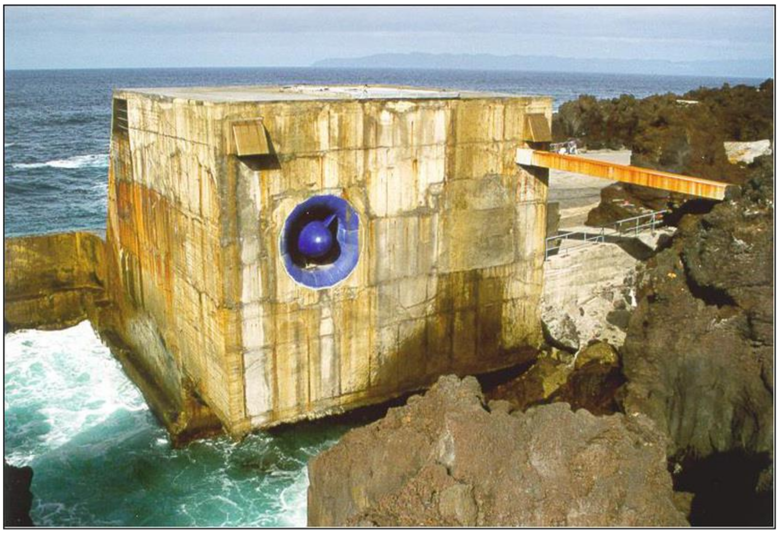


Figure 10: Pico plant WEC device

Regarding the Pico plant, the reliability issues reported below were detected (as per [34]):

- High vibrations in the turbo-generator;
- Power electronic equipment and transformers had to be renovated and relocated outside the plant due to the aggressive marine environment inside the plant;
- The guide vane stator on the atmospheric side of the turbine failed due to material fatigue.

Some of the above-mentioned reliability issues are owed to the continuous marine exposure of the different equipment of the device, but vibrations and failure of guide vanes are issues typical of the design. In fact, as stated in [34] "*the turbine design appears to follow the requirements for conventional unidirectional turbines and fell short to accommodate the conditions in a bidirectional, OWC turbine. The failure of the guide vane stator was attributed to pressure oscillations caused by vortex shedding under turbine stall conditions on the atmospheric side of the turbine. The problem was resolved with a new reinforced set of guide vanes*".

3) For the OceanLinx device, few operational information has been found. As reported in [34], the so called MK-3 device, a pre-commercial scale floating platform with 2 turbines, broke free of its catenary moorings and sunk in May 2010.

Figure 11: Oceanlinx WEC device

3.1.4.2.2 Point Absorber

Various point absorbers perform with linear generator. Archimedes Wave Swing (AWS), Trident energy and the Sea-based floating buoy developed at Uppsala University are just some examples of point absorber devices. After two failed attempts in 2002 and 2003, the 2 MW AWS prototype was deployed off the northern Portuguese coast in 2004. As stated in [34] "*during the deployment the control cubicle was flooded, and this led to the failure of crucial control and communication components"*.

While the AWS prototype emphasizes the challenge of offshore deployments and the careful planning it requires, it is nevertheless not informative about the reliability of linear generators in wave applications. One of the main reliability challenge for linear generators, as explained in [34], are "*the bearings that guide the translator and maintain the air gap between the translator and the stator. This is due to large attractive force between the translator and stator, the large amount of translator cycles for a typical year of operation and the fact that conventional mechanical bearings require regular maintenance. Plain contact polymer bearings are being investigated by who performed application specific testing of different bearing materials and point out the need to base the bearing system design on empirical test data*".

3.1.4.2.3 Hydraulic PTO System

One of the devices that employs this working principle is Pelamis (introduced in Chapter 2), which is made up of several partly submerged cylinders connected with hinged joints. As reported in [34], "*regarding the reliability of hydraulic PTO machinery, the following redundancies are apparent in the Pelamis configuration:*

- Three power conversion modules are operating independently (in parallel).
- Two generators rated at 125 kW each are installed within each of the three-parallel module.
- Two independent hydraulic systems, with one heave sway axis each.

In particular, the hydraulic cylinders are subject to reliability issues as they absorb the incident wave forces as a primary energy conversion step. They effectively act as compressing pistons which is contrary to their conventional deployment as actuators and results in much higher cycle frequency and reversed, less controlled loadings. Some of the detrimental effects that should be considered for hydraulic cylinders are:

- Fatigue and buckling of piston rod.

- Wear mechanism of seals, pins and bearings.
- Hydraulic fluid contamination (e.g. by seawater and bacterial growth).

High frequency oscillations due to the compressibility of the oil, significantly increase the travelled distance of the piston ring and thereby accelerate the wear of the ring seal. Moreover, average wear rates for different sea states are calculated. It is shown that the wear rate is affected by both significant wave height Hs and wave period Tp. During the deployment of three Pelamis machines in 2008 in Aguacadora, an increased wear rate was discovered for the main cylindrical bearings of the hydraulic cylinders. As a root cause undesired lateral movement of the bearing face has been identified and was not expected from preceding development testing. The design has been subsequently changed from the two axis hinged joints to a single universal joint, thus all bearings are on the same axis and are covered by a low-friction liner". The hydraulic PTO is a good example of the possibility of application of existing, studied and tested components to the WECs, but the modified loadings must be identified and understood in order to be taken into account correctly and ensure component reliability".

3.1.4.2.4 Overtopping (Water Turbine PTO)

The low head water turbines (already known and used in the hydropower plants), could also be implemented in overtopping WECs . In such technology, in fact, the wave movement pass through the device and water is gathered in an elevated reservoir that feed one or a set of turbines which in turn drives electric generators. An example of Overtopping device is the Wave Dragon (WD). Such Overtopping WEC, whose structural dimensions are large compared to the wavelength, has a potential rated power output up to 10 MW. According to [34], "*the device consists of three main components:*

- The main structure comprising ramp and water storage reservoir;
- Two wave reflectors fixed to the main structure, focus incoming waves onto the ramp;
- Several low head Kaplan turbines modified for variable speed operations.

Figure 12: Wave Dragon WEC Device

As the WD is a terminator-type device, the wave forces on the structure and moorings are expected to be large. After over 15,000 hours of sea trials with a 1:4.5 prototype, in January

2005 a force transducer in the main mooring line failed during a large storm and the device broke free. Nevertheless, the device has been at sea until 2011, and several reliability and maintenance issues have been identified:

- Turbine bearings were intruded by salt and began to corrode;
- The turbine draft tubes made from black steel and coated with epoxy paint experienced significant marine growth whereas a silicone based antifouling coating inhibited almost all marine growth;
- Maintenance activities on board and accessing the device could only be carried out in calm weather conditions most likely during the summer month;
- For electrical components Ingress Protection Rating IP66 (protected against dust and low-pressure jets of water) was not sufficient. The sea water spray overcame existing protections and attacked exposed sealing by corrosion" [34].

3.1.4.3 Conclusions on the Critical Components from the Literature Review

Considering the examples presented in the previous sections, it is possible to conclude that majority of the reliability issues observed are relevant to components belonging to the PTO sub-system. In particular, the hydraulic cylinders of the hydraulic PTO of Pelamis device was subject to reliability issues, mainly due to the fatigue and buckling of piston rod, the contamination by seawater or bacterial growth of the hydraulic fluid, and the wear mechanisms of seals, pins and bearings. The turbo-generator of the Pico Plant suffered as well, in terms of excessive vibrations.

Furthermore, a reliability issue spotted in many of the presented examples concerns the bearings. For both the point absorbers with linear generator introduced in Section 3.1.4.2.2, a well-known reliability challenge regards the bearings that guide the translator, while for the Wave Dragon device, the turbine bearings were intruded by salt and began to corrode.

Lastly, the mooring sub-system have been found critical in two devices analysed in the above-mentioned examples. The OceanLinx OWC device broke free of its catenary moorings and sunk while a force transducer in the main mooring line of the Wave Dragon Overtopping WEC failed during a large storm and the device broke free.

3.2 Industry Survey

As already described in the Methodology chapter (Subsection 1.3.2) of the deliverable, the purpose of the survey was to investigate, directly involving experts from the sector, which are the major critical issues, the best practices, standards, guidelines or technical specifications during the design/testing of the WEC critical sub-systems/components that may not have emerged through the literature review or that, on turn, could confirm the previous analysis.

The survey was shared by the project partners with their direct contacts and shared through personal and corporate social channels.

Twenty-two companies responded to the survey. 23% of the respondents are coming from outside EU, in particular from the United States of America (18%) and Egypt (5%). Another 23% are coming from Spain and then 9% from Denmark, Ireland, United Kingdom respectively. The survey also collected responses from France and Portugal (5% from each country) and Austria and Belgium (4% from each country). One company did not accept the GRDP Survey policy, and therefore could not respond to the survey.

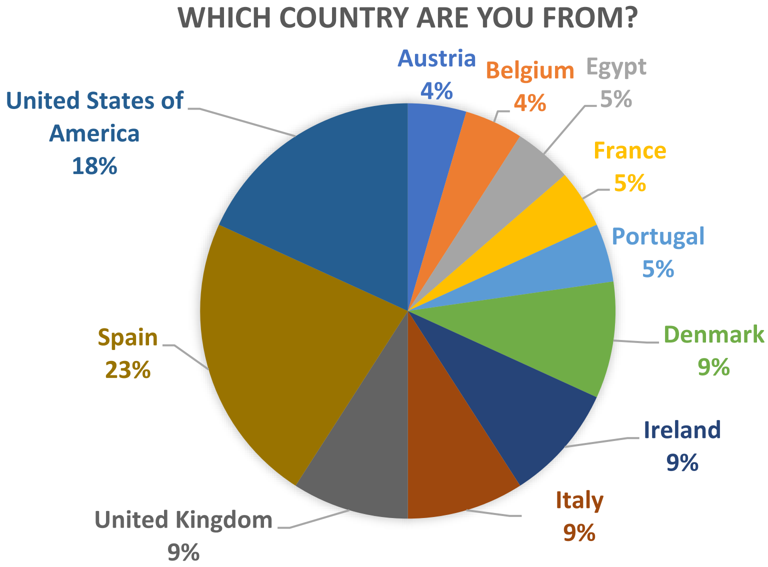


Figure 13: Which Country are you from?

3.2.1.1 Respondent Profile from the Survey

As shown in Figure 14, the respondents come have different profiles. About 36% are from consulting companies, 23% are wave technology developers, 18% are research organizations and 14% are Universities.

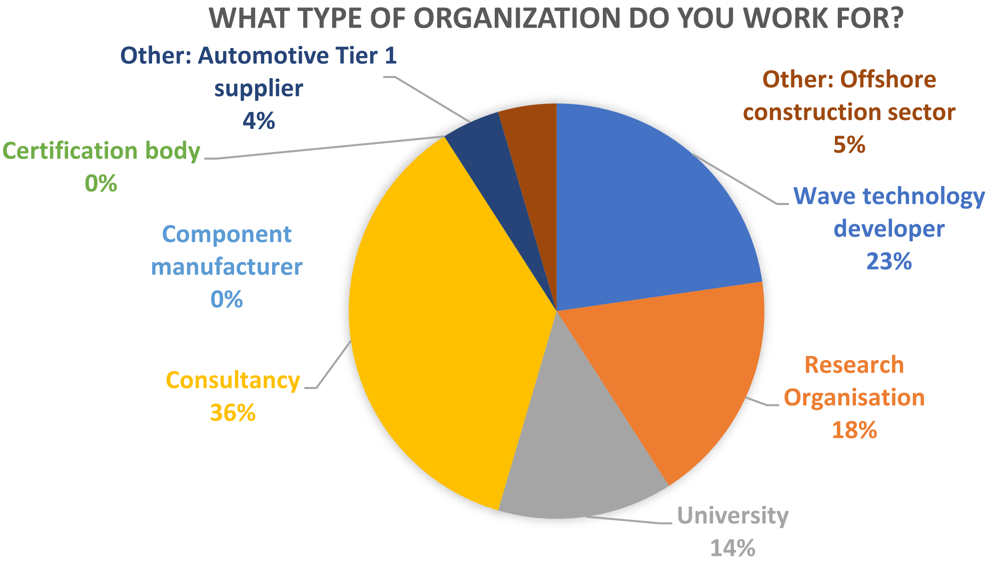


Figure 14: What type of organization do you work for?

Figure 15 depicts the main typology of WEC that is dealt with by the respondents. The type of WEC treated most by the respondents (about 28%) is the Point Absorber, followed by Attenuator and OWC which are treated by about 19% of the respondents. In addition, 14% of respondents deal with OWSC.

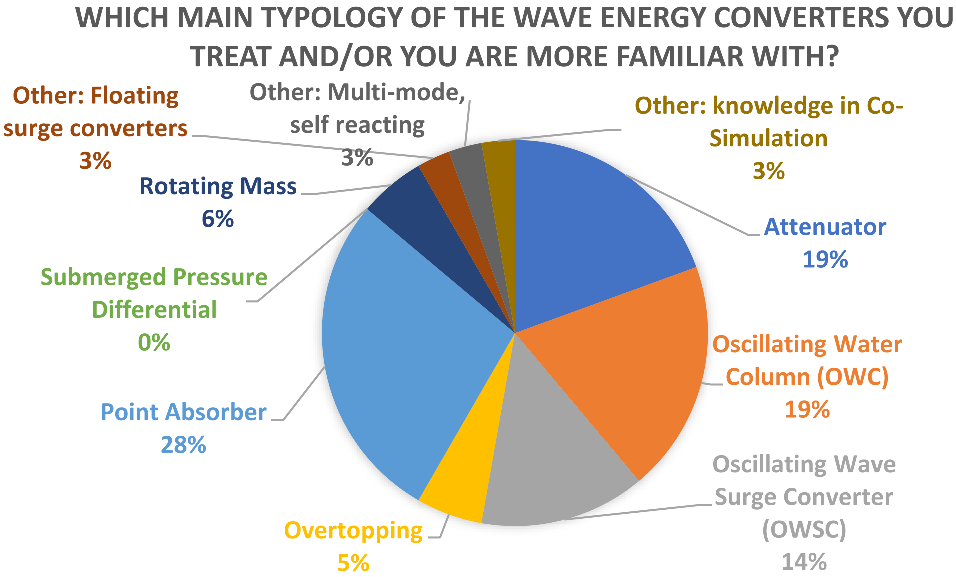
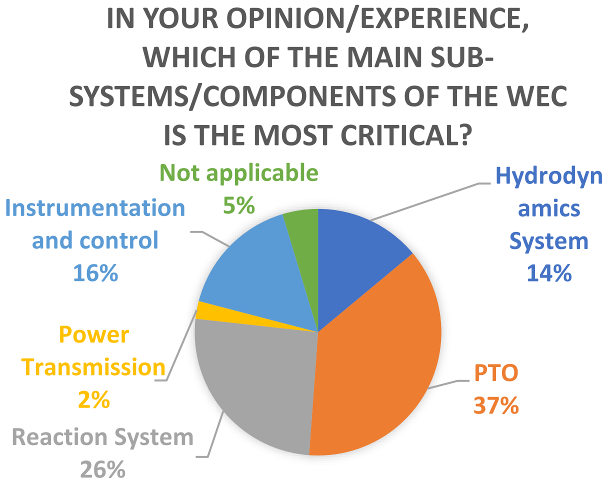


Figure 15: Which main typology of the wave energy converters you treat and/or you are more familiar with?

3.2.1.2 Technical Questions from the Survey

Subsequently, respondents were asked to share - according to their experience - which of the main sub-systems / components of the WEC is the most critical. Multiple choice was allowed. As shown in Figure 16, the survey highlighted that 37% of the respondents claimed to be the PTO sub-system, 26% claimed to be the Reaction System, 16% claimed to be the Instrumentation and control sub-system and finally, 14% claimed to be Hydrodynamics System. The Reaction System option also includes mooring systems (selected by 12% of the audience as a criticality).

Respondents who stated PTO, were asked to identify which type of PTO they found most critical, see Figure 17. 27% answered Hydraulic and Mechanical drive, 23% answered Air turbine, 20% answered Direct drive and 3% answered Hydro turbine.



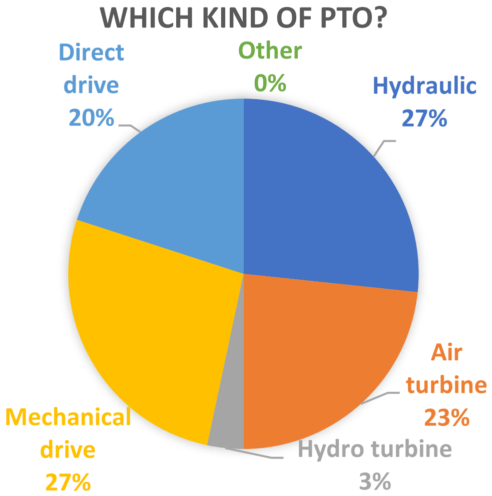


Figure 16: In your opinion/experience, which of the main sub-systems/components of the WEC is the most critical?

Figure 17: Which kind of PTO?

For the purpose of the VALID project, it was important to ask respondents if they refer to standards, guidelines or technical specifications when designing critical sub-systems/components. Multiple choice was also allowed in this question. As shown in Figure 18, the most selected option was "IEC TC114 technical specifications", as 38% of respondents chose it. Furthermore, 26% answered "Relevant certification bodies rules".

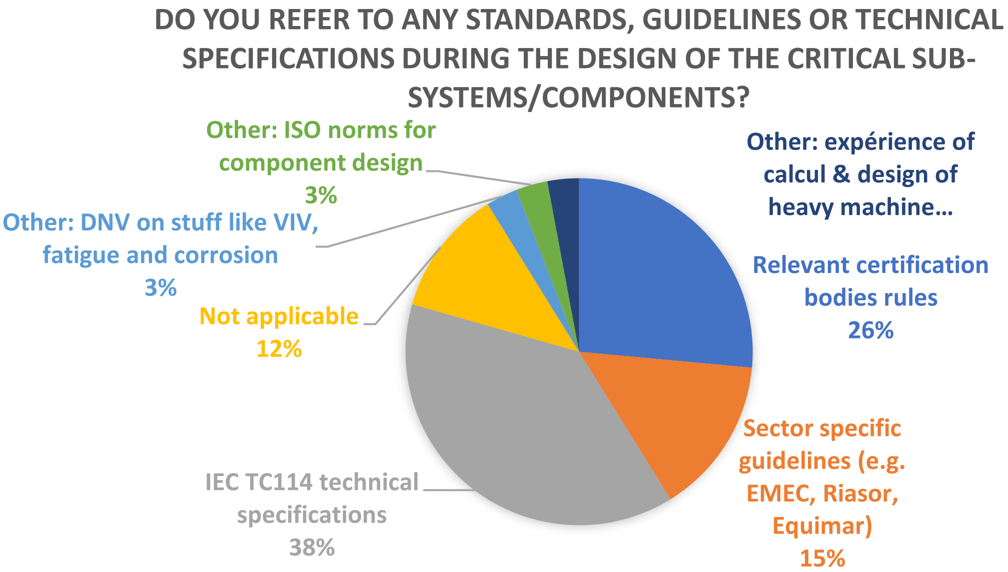


Figure *18: Do you refer to any standards, guidelines or technical specifications during the design of the critical sub-systems/components?*

As described in Section 3.1.3, there are several methodologies that are adopted to identify and prioritize critical sub-systems and components. The survey asked which of the most widespread and pre-identified methodologies is used by the respondents - also in this case the multiple answer was possible. As illustrated in Figure 19, the most used methodology according to the survey is FMECA/FMEA (52% of the answers). With a score of 26%, it emerged that HAZID / HAZOP is also a widespread and used methodology.

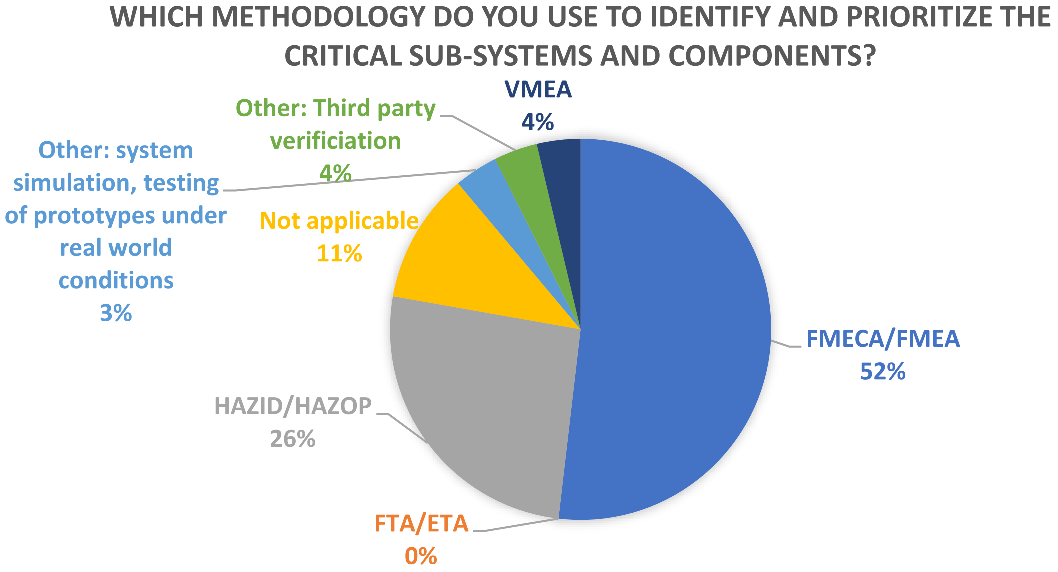


Figure 19: Which methodology do you use to identify and prioritize the critical sub-systems and components?

Critical sub-systems can have a major impact on WECs performance, survivability and reliability among others. For this reason, respondents were asked to highlight which, according to their opinion/experience, is the main impact that is encountered. It was possible to select a multiple choice; results are illustrated in Figure 20. According to 40% of the audience, critical sub-systems impact the reliability of WECs, increasing OPEX due to an increased need for maintenance. According to 32% of the respondents, critical sub-systems impact WEC performance, leading to a loss of power production. According to 22% of the respondents, critical sub-systems impact WEC survivability, as they could lead to severe damage and/or loss of the asset.

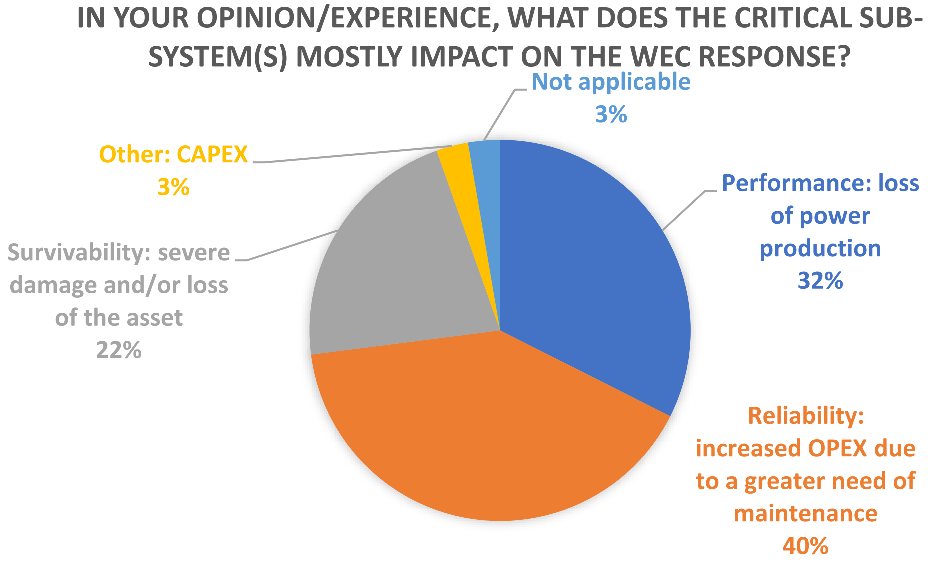


Figure 20: In your opinion/experience, what does the critical sub-system(s) mostly impact on the WEC response?

The following question dealt with the tests that are routinely performed on critical subcomponents (multiple choice was allowed). Figure 21 provides an overview of the replies of the respondents.

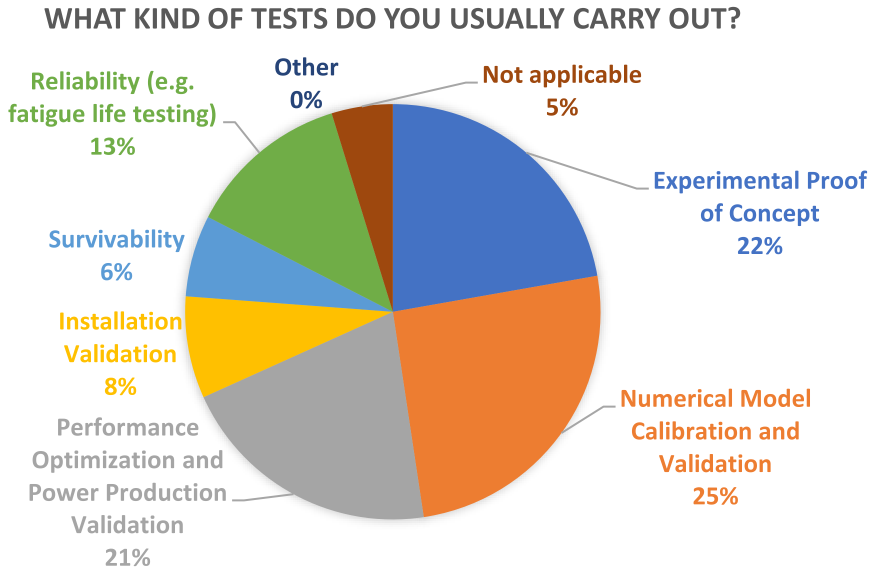


Figure 21: What kind of tests do you usually carry out?

Another question was related to which WEC TRL respondents would test component reliability at. This is a very important question for understanding testing procedures. As shown in Figure 21, not all respondents (30% of them) were able to provide details probably due to their knowledge or role in the company and therefore selected the "Not applicable" option. Furthermore, 45% of the audience said they would test components when they are in the Design Optimization and Scale Demonstration phase (TRL 4-6), while 15% would test components during the commercial scale demonstration phase in the operational environment (TRL 7-9). The remaining 10% would test during the Concept Creation and Development phase (TRL 1-3).

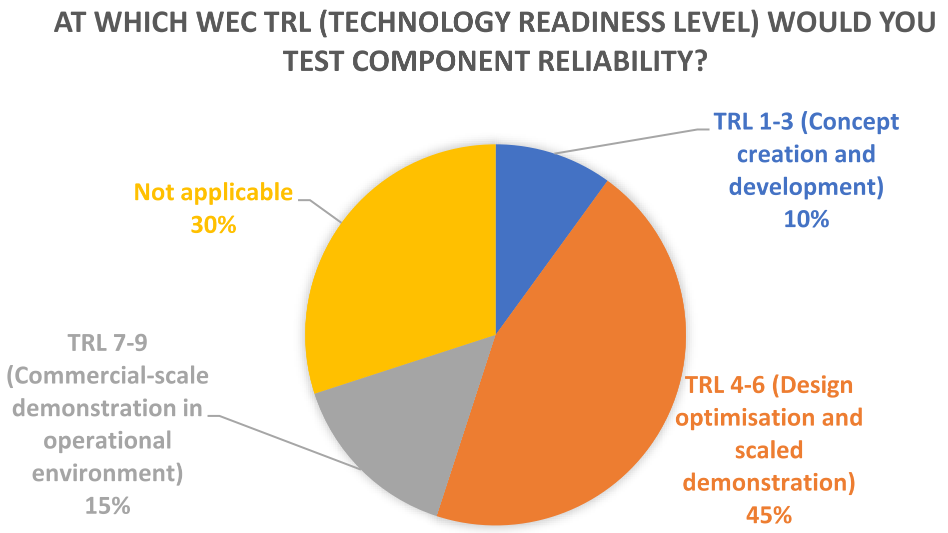


Figure 22: At which WEC TRL (Technology Readiness Level) would you test component reliability?

It was also investigated if usually the sub-systems / components the respondents deal with are tested with accelerated life tests. As shown in Figure 23, many respondents (45%) could not provide an answer. On turn, 40% of them do not routinely carry out tests with accelerated life tests while 15% do. Those that replied "yes" were asked to provide a brief description of the type of accelerated test that is normally performed. The answers were the following:

- Fatigue testing of belts and restoring force mechanism;
- For (automotive) engines durability: 100h full load test;
- Full scale structural load tests - Design load static and accelerated fatigue life;
- Dynamometer testing of PTO at full scale where possible with simulated inputs.

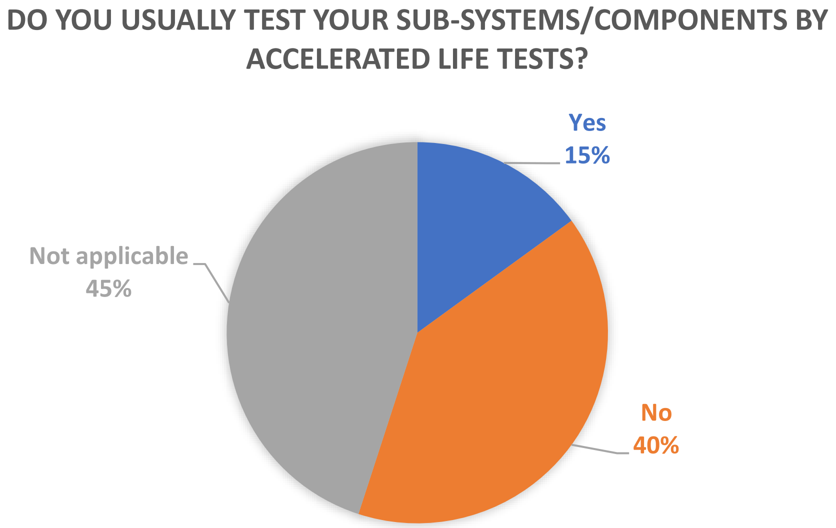


Figure 23: Do you usually test your sub-systems/components by accelerated life tests?

Finally, respondents were asked if they were interested in hybrid testing for their developments. As shown in Figure 24, 67% of the audience confirmed its interest.

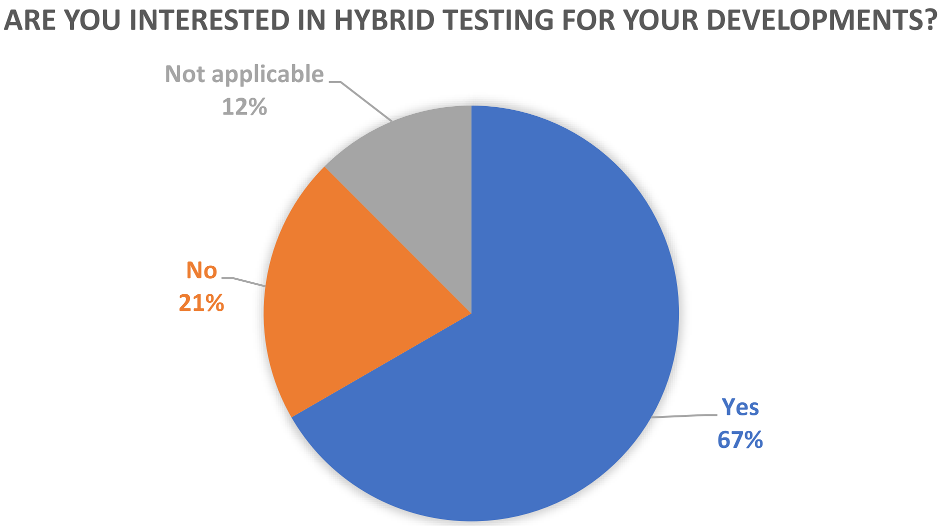


Figure 24: Are you interested in hybrid testing for your developments?

3.2.1.3 Conclusive Open Question from the Survey

The final question included in the survey gave us the opportunity to leave free word to the respondents to provide further details on their opinion about the reliability and survivability of the components and sub-systems that form WECs.

Three of them provided the following details / precautions:

- Avoid complexity and have on-board redundancy.
- Reliability and survivability are linked to the WEC design.

- For PTO: the less moving parts in direct contact with waves, the better.
- WEC with underwater/seabed parts (Oyster and the like) will experience high OPEX costs.
- Any WEC having a weight-to-capacity ratio (ton/MW) > 200 ton/MW will unlikely deliver a high capacity factor because heavy structures lead to high CAPEX and OPEX.
- The entire prototype WEC system should be open water tested in an aggressive environment for at least one storm season to verify the reliability of the entire system.

3.2.1.4 Summary of Results and Conclusions

Through the survey, it was possible to collect different opinions from the experts in the sector that allowed to enrich the analysis performed through the literature review and to achieve additional and interesting conclusions for the purpose of the VALID project.

First of all, the WEC types treated the most by the respondents are the Point Absorber (28%), the OWC (19%) and OWSC (14%). The WEC market is composed by a much wider range of companies than those that participated in the survey, but based on the population of the survey participants, it can be inferred that the three User Cases (User Case I is a Point Absorber, User Case II is an OWC, User Case III is an OWSC) that have been included in the VALID project fall well within the interest of the survey respondents.

Subsequently, the respondents identified, based on their experience, which sub-systems/components of a WEC might be most critical. The survey showed that the PTO is considered the most critical (37%) together with the Reaction System (26%),the Instrumentation and control (16%) and the Hydrodynamics System (14%). It is important to underline that the Reaction System option also includes the Mooring Systems, option selected by 12% of the audience. According to what emerged in the previous section, the components belonging to the PTO sub-system report the greatest reliability problems, therefore the result of the survey is in line with the literature review performed. It should be borne in mind that WEC technologies are relatively new and for this reason it is more difficult to find numerous references on PTOs with which to compare the survey. On the contrary, it was possible to find at least two examples in which the mooring sub-system was found to be critical from the literature review. The mooring system for WECs, and in general for all offshore technologies, recovers experience from the Oil & Gas sector and for this reason it is possible to find more examples / studies / analyses in literature.

Subsequently, respondents identified the standards, guidelines or technical specifications to which they refer most when designing critical sub-systems/components. 38% refer to "IEC TC114 technical specifications", while over 26% refer to "Relevant certification bodies rules".

According to the respondents, the most used methodologies to identify and prioritize critical sub-systems and components are FMECA/FMEA (52%) and HAZID/HAZOP (26%).

According to the audience, critical sub-systems affect the reliability of WECs (40%), increasing OPEX due to increased maintenance requirements, WEC performance (32%), leading to a loss of power generation, and on WEC survivability (22%), as they could lead to severe damage and / or asset loss.

Furthermore, the survey revealed that 45% of the audience would test components during the Design Optimization and Scale Demonstration phase (TRL 4-6), while 15% would test components during the commercial scale demonstration phase in the operational environment (TRL 7-9). Only 10% would test verification during Concept Creation and Development phase (TRL 1-3). This information is important for the VALID project because it confirms that there is room for improvement on low TRL tests. The VALID project will develop a hybrid testing platform that enables accelerated test procedures at lower readiness levels in order to improve the reliability and survivability of the components and sub-systems.

At the time of the survey, only 15% replied to test sub-systems/components with accelerated life tests, while 40% do not regularly perform this type of test.

The VALID project must aim for that 40% who still do not perform these types of tests today. It is interesting how 67% of the audience is interested in hybrid testing for the development, confirming once again how fundamental the activities that will take place in the VALID project are and how its result is a platform that can be exploited by the reference sector.

3.3 High-Level Analysis: User Cases

This section aims at providing a high-level introduction to the VALID User Cases, which will be further detailed throughout the VALID project, in particular in WPs 3 to 5. In each of the following sub-sections, a summary table with a general description of the relevant user cases will be presented. A template table to collect information in a standard format (see Table 11) was circulated with the WECs developers of WP3 (CorPower), WP4 (IDOM) and WP5 (Wavepiston). Particular attention was given to the methodology adopted to identify the most critical sub-systems and components.

Table 11: High-level description of the user-case - template

User Case	User case identification
Key Sub-System	E.g. PTO, Prime Mover, …
Key Component(s)	Within the key sub-system, what component(s) is (are) critical?
Criticality Description	Why are the sub-system and components critical? In the context of the WEC, what does they interact with?
Criticality Identification Method	How was its criticality identified / assessed?
Current Design Best Practices	How the critical sub-systems are designed in order to avoid criticalities? Which are the best practices in the design phase for the critical components?
Current Models / Test Rigs / Platforms /	Has the critical sub-system been tested? Theoreticality / analytically, numerically, experimentally (if so, at what scale?), and / or in the ocean (if so, at what scale)? Has hybrid testing taken place in a platform (i.e. critical physical sub-system interacting with simulation of other sub-systems and / or complete WEC model?) Please describe.
Planned Adaptations to Current Status	Are there any identified gaps in the current models / modelling platforms?
Initial Thoughts for	E.g. thoughts on necessity of critical sub-system being represented at full-scale, regardless of whatever else is hybrid; what can be numerical in testing platform?

Testing Architecture	

3.3.1 User Case #1: CorPower

The User Case #1 is addressing failures in the dynamic sealing systems of a pneumatic PTO. The latter is one of the key components of a point absorber WEC developed by CorPower.

During an earlier H2020 project, WaveBoost, several components of the sealing systems were identified as critical. The novel methodology developed in VALID will be applied in CorPower's physical test rig for seal testing. It is being customised and rebuilt to enable improved understanding of scale effects, sea water exposure and various types of rod coatings and sealing components. The seals are highly dependent on that the surface of the rods are kept in good tribological condition. They are subject to wear due to, among others, surface roughness, speed, temperature and lubrication. The main concerns that were identified were marine growth, corrosion and wear. Some tests were carried out at the end of the WaveBoost project, but it was concluded that a more comprehensive and thorough study was necessary to catch parameters' dependencies and reach satisfactory reliability levels.

Table 12: High-level description of the user case #1: CorPower

User Case	CorPower: PTO
Key Sub-System	Dynamic sealing systems, components under reciprocating loads.
Key Component(s)	Seals, mating rod surfaces, guiding systems, lubricating oil, high pressure air.
Criticality Description	Interaction with high-pressure air systems, vital for the WEC (to avoid leakage). Interaction with corrosive environment. Potential contributor to PTO losses (friction). Guiding/positioning functions ensuring WEC's integrity. Unique combination of tough requirements and long maintenance intervals needing high component reliability.
Criticality Identification Method	FMECA, combined with engineering judgement and knowledge of similar industrial systems. Previous project WaveBoost initiated reliability/performance studies on these components.
Current Design Best Practices	Careful selection of materials and design of critical components. Ensuring that the specificities of the application are well understood by suppliers. Discussing with several suppliers to get an understanding at system-level, rather than focused on specific components. (e.g. "tribological system" instead of "seals").

Current Models / Test Rigs / Platforms /	CorPower operates a complex Wave2Wire numerical model that implements all parts of the power conversion, from wave models, primary converter (WEC hull), through mechanical PTO (linear to rotary), electrical generation conversion, and power export. This numerical model is constantly calibrated by testing the performance of components, sub-systems (modules) and full WEC systems. These tests consist in a mix of: • "dry testing" in the lab (ranging from small manual test setups to full, multi-megawatt PTO-in-the-loop test rigs); • "ocean testing" by component exposure tests (biofouling, corrosion tests) and full WEC deployments (1/2 scale WEC in 2018, full-scale in 2021). The PTO-in-the-loop rigs that CorPower uses are a typical example of hybrid testing. They have actual wave data as input to the controller, which converts it into theoretical hydrodynamic loading and then applies corresponding physical loads to the tested PTO. The WaveBoost project created a dedicated rig for testing of reciprocating components like dynamic seals, that CorPower is still owning and willing to use in the VALID Project. This rig was for example used to create multiparameter, comprehensive friction and leakage models that were used to calibrate the "top" Wave2Wire model. Some parts of the Wave2Wire models are being replaced/complemented with Machine Learning algorithms, which have proved to bring substantial optimization potential. All these numerical models are typically used for safety and performance analysis/predictions, but so far, failure modelling/prediction has not represented a large part of them.
Planned Adaptations to Current Status	Platforms are essentially blind to failure predictions/ reliability monitoring due to lack of data / testing. Use of Machine Learning can be developed and bring performance improvements (wave prediction, controller tuning, etc.) and reliability improvements (failure prediction).
Initial Thoughts for Testing Architecture	Revive the reciprocating "seal test rig" and adapt its software /data acquisition system to collect data in a usable way for training of machine learning algorithms. Trigger artificial, highly accelerated failure modes or virtual data representing them.

3.3.2 User Case #2: IDOM

The User Case #2 is the Electric Generator failure. For the purposes of this project, this failure mode will be exemplified on IDOM's OWC device MARMOK. The generator of this WEC has been extensively tested at the Mutriku shoreline OWC plant (12 months) and at the BiMEP open-sea testing site (3 winters, the last within the Horizon2020 OPERA project with a new turbine).

Through this user case, the VALID project will validate how the proposed methodology can assist in the understanding and evaluation of failures in generators and power electronics that in the most energetic sea state operate about 20% of the time over nominal power. This type of operating pattern is typically found in OWCs, both floating and fixed.

In Table 13 a description of the User Case #2, that will be subject of WP4 of VALID project is reported.

Table 13: High-level description of the user case #2: IDOM

User Case	IDOM: Testing of electric generator failure
Key Sub-System	Power Take-Off consisting of an air turbine, electrical generator and power electronics
Key Component(s)	The electrical generator insulation failure is a significant root cause for the breakdown of high voltage rotating machines. The ageing mechanism is dominated by thermal degradation of the binder resin, mechanical stress caused by vibration and switching pulses and stress caused by the different thermal expansion coefficients of the materials involved. Tightly coupled with the electrical generator, the power electronics suffer similar issues. Moreover, the power peaks and the environmental conditions impose very severe conditions on the mechanical design of the generator: bearings, balancing, alignment, etc.
Criticality Description	The electrical generator is in the critical path of the energy conversion steps. It is the core of the WEC where mechanical energy is transformed into electrical power. A failure in this component will directly reduce the Annual Energy Production (AEP) which creates incomes for the wave energy plant. Wave Energy devices are not usually easy to be maintained on site due to the constrained working conditions on board (i.e. weather windows, movements and accelerations, reduced working space, etc.). If towed onshore for maintenance, the downtime and the maintenance cost increase significantly.
Criticality Identification Method	This failure was experienced during the testing of the new turbine-generator set in the OPERA project. Tests were performed at the Mutriku Wave Power Plant, infrastructure belonging to BiMEP, where the failure occurred. Having this failure been experienced in the open-sea deployment, the demonstration would have been seriously compromised.
Current Design Best Practices	Extra insulation is used to prevent premature failure but increases cost of rotor and stator. It is important to consider whether the thermal stresses are constant or present for only a brief time, i.e. they are transient. If deterioration is primarily due to transients, then the time to failure is proportional to the number of transients the generator experiences.
Current Models / Test Rigs / Platforms /	As described above, the failure was experienced during the shoreline testing of the new PTO. The prototype for the open-ocean demonstration was of limited power compared with the full scale in order to reduce the investment costs for this validation phase of the wave energy technology. Nominal power of the electrical generator was 30 kW compared with the expected full-scale 250-300kW.

	In the testing of the OPERA project turbine in Mutriku an analyser was installed between the generator and the power converter, and transients of 1kV were observed. The Mutriku Wave Plant provided all physical infrastructure to test the PTO without the need of any virtual part. Obviously, the wave resource was not exactly equivalent to the one at the deployment site but provided us with environmental factors such as humidity and salinity. Originally, the tests were not designed for reliability, as they lack the flexibility of a control environment and could not be accelerated.
Planned Adaptations to Current Status	Wave-to-torque models have been implemented and validated by IDOM. TECNALIA has modelled voltage peaks in the generator within one of the DTOceanPlus design tools, namely Energy Transformation. However, transient effects still need to be fully validated with laboratory testing. The current infrastructures/rigs require the installation of further sensors and instrumentation to monitor relevant parameters.
Initial Thoughts for Testing Architecture	Testing of the generator at full scale is not considered to be a critical requirement, since wave energy devices will have a broad range of nominal powers depending on the deployment site, the specific technology or even the configuration of the PTO (i.e. single or multiple turbines per device). However, some phenomena may not be fully scalable. There is a more fundamental question of how to combine in a controlled laboratory environment the environmental loading which can accelerate the degradation of the insulation under certain conditions. The analysis of generator performance under specific stress conditions requires the installation of sensors to monitor relevant parameters. Accelerated aging tests will require increasing the stress levels above normal service operation conditions. This could either involve increasing the ambient temperature where testing is performed or under sizing of ley components to speed up the failure.

3.3.3 User Case #3: Wavepiston

User Case #3 relates to the Hydraulic Pump failure, relevant to the Hydraulic PTO and exemplified by an Oscillating Wave Surge Absorber, developed by Wavepiston. Potential failures have been identified in the functioning of the pump sequencing mechanism, as well as in the seals and glider rings of the pump. The linear and reciprocating back and forth movement of the pump is activated by the energy collectors placed over the common string following the motion of the waves.

For the purposes of this project, this failure mode will be exemplified on the Wavepiston device, which has been extensively tested in open-sea at DanWEC test site (Denmark) in scale 1:4 to 1:2 (several iterations over 3 years) and also extensively dry lab tested. Wavepiston have deployed a first version of the full scale WEC in late 2020 at Plocan, Gran Canaria, following up with more installations in 2021[8].

Table 14: High-level description of the user-case #3: Wavepiston

User Case	Wear and tear on high pressure seal

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[8] https://www.plocan.eu/en/wavepiston-installs-a-wave-energy-converter-at-plocans-test-site/

Key Sub-System	PTO
Key Component(s)	For robustness the Wavepiston PTO system relies on generation of pressurized water. The main component of the PTO system is two counteracting hydraulic rams. Due to the design philosophy of Wavepiston, minor leaks have no detrimental effect on the system The critical component(s) in these rams are the sliding seals that in the Wavepiston implementation are fully immersed in water and (if lubricated at all) relies on seawater for lubrication, cooling and removal of particles
Criticality Description	This is the main PTO component of the system. If this component fails, the system will fail its main objective as energy producing device. Furthermore, loss of system pressure will reduce the damping action of the PTO which will strain the prime mover beyond design limits.
Criticality Identification Method	FMECA
Current Design Best Practices	Until now Wavepiston has relied heavily on the experience of the supplier for choosing the best seals.
Current Models / Test Rigs / Platforms /	Seal testing has been carried out at the supplier.
Planned Adaptations to Current Status	The tests have not had the erratic variations in speeds and stop/go action of a real system nor does the current test system allow for pump (seal) reversal in random places along the pump stroke. Thus the current setup gives non-realistic tribological wear conditions in the most critical zone (i.e. during pressure build-up and start). Furthermore, environmental impact such as marine growth, sand particles, UV exposure and so on has not been addressed.
Initial Thoughts for Testing Architecture	Wavepiston wants to build a universal testing ring which should emulate the tribological parameters of real sea wear and tear.

4 High-Level Accelerated Testing Limitations and Requirements

After having defined most of the sub-systems and components of different typologies of WEC devices, in the following sections the concept of accelerating testing procedure as technology development asset is introduced. In particular, the used methodologies and reliable procedures are presented, including major advantages and limitations.

The whole section starts with a description of the most relevant aspects for a successful design phase within WECs framework, highlining the key objects of a WEC design process. After this, in Section 4.2, the concept of accelerated testing is introduced, also mentioning the different purposes that such methodology may have (early stage design, detailed design, verify design). Section 4.3 describes different methods to accelerate tests, that are needed to save time and/or cost, and the different possibilities include increasing the usage rate, increasing load magnitudes, severe environmental conditions, and reducing the resistance of the test specimen. Additionally, overstress testing methods are described in some more detail in Section 4.4. Finally, in Section 4.5 a specific focus about accelerating tests applied to most common industrial branches is provided (i.e. oil & gas, wind turbines) and in Section 4.6 the most useful legal references in the sector are reported.

4.1 Design Load Cases

The methodology that defines the load and strength assessment of an offshore renewable energy converter is typically underpinned by a set of Design Load Cases (DLCs). These can be defined as combinations of operational modes and / or design situations with external conditions, providing a succinct representation of key input parameters that define relevant loading scenarios to be experienced by the structure during its design life.

In more established fields such as offshore wind, dedicated DLC tables have been widely available for more than a decade, with recent updated versions addressing specifically fixed and floating offshore wind concepts – for up-to-date guidance see e.g. [35], [36] and [37]. Despite the commonality with the offshore wind sector, the introduction and definition of DLCs in wave energy is relatively recent, with only a short number of references offering detailed insight. These include:

- IEC TS 62600-2 [38], where essential design requirements related to the integrity of wave and other marine energy converters (MECs) are overviewed for a specified design life. All key sub-systems as listed in Section 2 of this report are addressed. Safety factors and design methods are also overviewed. A specific DLC table for WEC design is provided.
- The WES Structural Forces and Stresses Landscaping Study [16], where the design process of (more) conventional offshore structures is adapted to WEC design, from a loading and strength assessment perspective. Starting from a review of relevant guidelines and standards from related industries, the importance of comprehensive design methodologies that cover a range of performance, reliability and survivability related design situations from an early stage is emphasised. Descriptive examples of assessments are given, for multiple WECs, including high-level FMECAs that allow the shortlisting of priority DLCs. Additionally, detailed DLC descriptions and a dedicated WEC DLC table are also provided.

Conceptually, and in alignment with [16] and [38], throughout the design process the integrity of a WEC design shall be assessed considering the following combinations[9]:

- Normal design situations and normal external conditions[10].
- Fault design situations where the WEC is operating with a single major system failure, under appropriate external conditions.
- Normal design situations and extreme external conditions.
- Design situations for transportation, installation, maintenance and decommissioning (and the appropriate external conditions).

Table 15 summarises the range of design situations proposed in [16], and the associated recurrence period. Specific DLCs within each design situation can also be related with a design category (e.g. Normal, Extreme, Abnormal, Transport & Installation), which in turn can be linked to a partial safety factor that addresses both load uncertainty, including that associated with the loads model, and the respective probability of occurrence. These partial safety factors are typically applied to the characteristic load values in an Ultimate Limit State (ULS) context, with partial safety factors of 1.0 being applied to all other relevant limit states. It should be noted that for other limit states, additional factors may be applicable – e.g. Design Fatigue Factors (DFFs) in the context of estimating the design fatigue life.

Table 15: Representative design situations in WEC design (adapted from [16])

Design Category	Recurrence Period	Design Situations
Normal (N)	≤ 1 year	• Power production • Power production plus occurrence of a fault • Start-up • Normal shutdown • Emergency shutdown • Parked / Survival (standstill or idling) • Parked / Survival plus fault conditions
Extreme (E)	≤ 50 years	• Power production • Parked / Survival (standstill or idling) • Parked / Survival plus fault conditions
Abnormal (A)	≤ 500 years	• Survival events (if not covered in any of the other load cases) • Damaged stability
Transport and Installation (T)	≤ 1 year	• Transport, installation, maintenance and repair

An example of a representative DLC table for WECs is provided in Appendix B. Detailed load case descriptions compatible with Appendix A can be found in [16] and [38].

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[9] Additionally, and if a correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a DLC.

[10] The term 'external conditions' encapsulates both environmental conditions and other additional events (e.g. grid fault).

When considering the creation of a novel hybrid testing methodology for WECs, it is important to frame the relevance of a DLC table in the context of the WEC design process' timeline. Following [16], and at a high-level, the timeline of the WEC design process can be associated with three main stages:

- Design basis.
- Concept design.
- Detailed design.

These stages are illustrated in Figure 25, where an outline of the key objectives and tasks associated with each stage is also given.

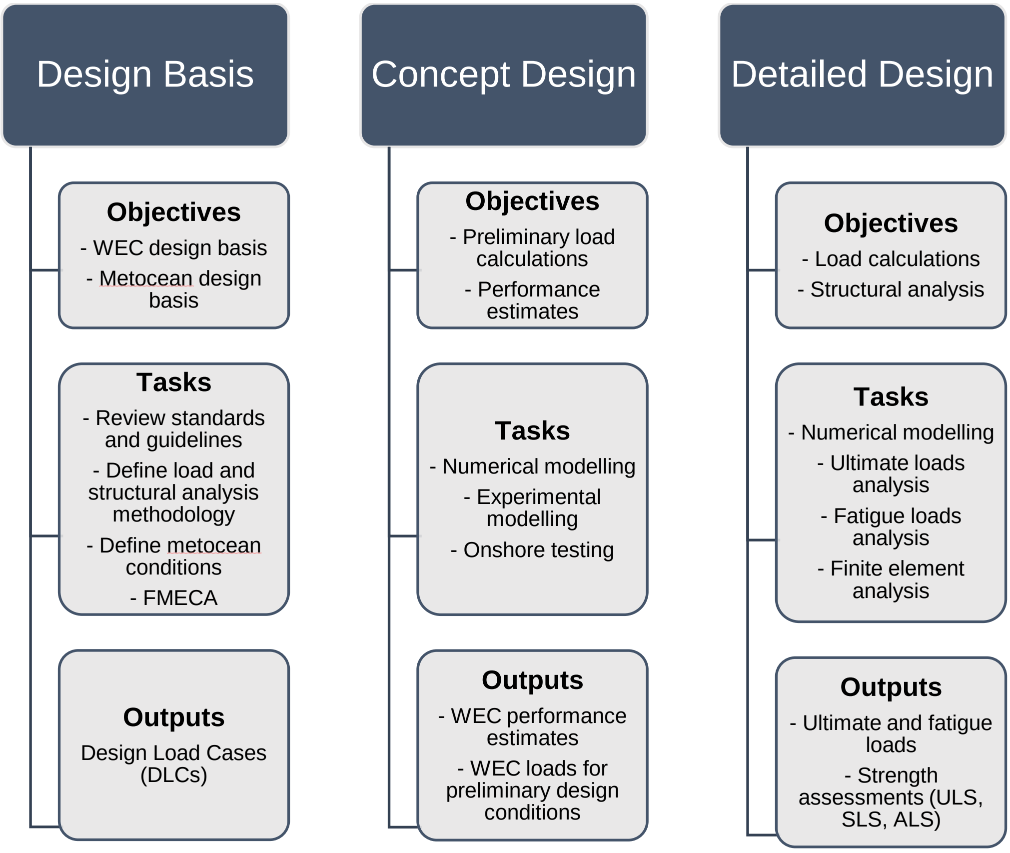

Figure 25: Key objectives and tasks: WEC design process [16]

As Figure 25 illustrates, the creation of a design basis document is at the inception of the design process. A design basis document will remain applicable throughout the design process, thus guiding concept and detailed design studies. Typically, load and structural integrity assessments are conducted at both the concept and detailed design stages, ultimately for a complete set of DLCs, covering e.g. fatigue (F) and ultimate strength (U) scenarios.

Additionally, and again following Figure 25, a key output of the design basis stage is the definition and selection of DLCs, which can then be used (and eventually updated) in subsequent design stages. At a conceptual design level, some DLCs may be excluded depending on the actual WEC and / or on specific site conditions, e.g. if certain environmental conditions do not apply (seismic effects, ice, etc). Furthermore, at this initial stage the compilation of a shortlist of priority DLCs should be preceded by a risk assessment, conducted via e.g. a FMECA study targeting all critical sub-systems – see also Sections 1.3.3 and 5.

Such approach leads to the selection of the DLCs that are most critical to the design stages of interest, allowing the conceptualisation of a specific design methodology adjusted to both the test objectives and to the level of detail associated with the design stage in question. It is therefore of paramount importance that a design basis document (or equivalent, e.g. a design brief) is considered when planning a hybrid test campaign, justifying, and defining inputs, objectives and methodologies, and summarising these in a set of clear DLCs.

A preliminary discussion concerning the creation of key documentation and the definition of DLCs in the context of a hybrid testing methodology framework will be introduced in VALID's D1.2. However, and in addition to the general notes presented in this sub-section, specific aspects related to accelerated testing may influence the adaptation of key inputs to critical DLCs; such aspects are addressed in Section 4.2.

4.2 Accelerated Testing Methodologies

The requirement of the accelerated testing depends on the stage in the design process. Accelerated reliability testing is often divided into three types of tests:

- Highly Accelerated Life Test (HALT), where the goal is to find weak spots in the design and is often appropriate in the earlier design stages.
- Characterization test, where the purpose is to characterize the properties of the system/component and is typically preformed in the detailed design stages to give input to the strength assessment.
- Verification test, where the purpose is to verify that the system/component fulfils the requirements and is carried out in the last phase of the detailed design stage.

These three types of accelerated testing methods will be detailed below. Testing methodologies for censored data and when measuring degradation is then discussed. In Section 4.3 different acceleration methods will be reviewed.

4.2.1 Highly Accelerated Life Test (HALT)

Highly Accelerated Life Testing, HALT, is based on the idea that failures give more information than non-failures. Hence, this method does not regard survival of the test object as a success, but designs tests with the purpose of failure, regardless of what severities are needed, even if they are far beyond specifications. An advantage is that HALT is designed to give as short as possible testing times. A limitation of the HALT method is that a highly accelerated life test may cause failures by other mechanisms than the ones that are of interest. Therefore, the resulting failures should be analysed critically, and the following questions should be asked:

1. Could this failure occur in service?
2. If so, could it be prevented from happening?

In most cases the time of tests are the main cost driver. The HALT method is in this sense relatively inexpensive, as it forces failures to happen in a short time and gives rise to continuous improvements of the design. In contrast, tests at expected severity, "verifying" that the construction survives, are expensive, time consuming and are not likely to discover weak spots that may cause failure at extreme events in service.

4.2.2 Characterization Test

A characterization test is an accelerated life test that is designed to elaborate models and dependency of influencing factors, e.g. pressure, temperature, speed, surface roughness, etc in the case of dynamic seals on a rod. Hence, the testing should be designed to generate the same kinds of failure modes that are expected in service. The goal is to characterize the life model, and especially to predict life for real conditions using mathematical and statistical models derived from the testing.

4.2.3 Verification Test

The goal of a verification test is to verify that the design targets are fulfilled using loads that are representative for real conditions. Thus, the accelerated testing is performed making sure the test is representative for operational condition. The aim is to verify that the component, sub-system or full system satisfies the reliability requirements, and if possible, also to predict real lifetime. This kind of test is also called sign-off test or release test.

4.2.4 Tests with Censored Data

For higher reliability components, data from the upper tail of the life distribution provides little information. The main interest is then on the lower tail. Censored tests are basically terminated before all parts being tested fail, which consequently shortens overall test time. However, sometimes an important failure mode is active at the design stress level, does not occur in the lower tail, but in the upper tail. Therefore, terminating the test early would miss that important failure mode. Unfortunately, the test information acquired from censored tests is limited: either pass or fail against a desired reliability goal. The actual strength distribution of the product is not determined and, if the component passes, there is no information to improve the product.

Often verification tests are designed as censored tests with the hypothesis that the component has a given reliability with a given confidence [39]. The hypothesis is tested by determining how many parts should last for a given period of time at a given severity with no failures. The precision of this method depends on the number of parts being tested. The higher the number of parts that pass the test, the lower the number of parts required.

4.2.5 Tests Measuring Degradation

In this kind of tests, component performance is observed as it degrades over time. A model for performance degradation is fitted to such performance data and used to extrapolate performance and time-to-failure. Thus, the failure and life distribution can be predicted before any component fails which accelerates the test. Failure is assumed to occur when a component performance degrades below a specified threshold value. For example, the breakdown voltage of insulation parts at high temperature can be measured at various aging conditions. In this case, the insulation can be considered to fail when its breakdown voltage degrades below the design voltage.

4.3 Acceleration Methods

The target life of a WEC is typically 20-25 years, and, thus, reliability tests must be accelerated in some way to get reasonable testing times. Hence, there is a need for methods to accelerate tests so that tests can be performed in a shorter time and/or at a reduced cost. The appropriate acceleration method and the amount of acceleration depends on several factors, e.g.:

- The type of material(s) of the component or structure that is tested,
- The type of load variables that are considered (e.g. mechanical or electrical load),
- The type of failure mode that is considered,
- The frequency response to load excitations of the component or structure.

Thus, the acceleration methods used in a specific case need to be adapted to the properties of the specific component or structure to be tested. We will here give a general review of different methods for acceleration of testing, see e.g. [4], [7] and [8].

The methods below are often combined in order to get an efficient acceleration. However, different acceleration methods may interact resulting in an even larger acceleration in combination, e.g. the combination of corrosion and mechanical loads will most probably result in an even higher acceleration. Note that the acceleration methods can be implemented both in the physical environment (to decrease the time of experimental testing) and in the virtual environment (to decrease the time of numerical computations).

4.3.1 Time Acceleration (High Usage Rate)

A simple way to accelerate the degradation of many components is to increase their usage rate. Usually, such compressed time testing can be achieved through a faster running speed or reducing the off time. However, the test must be run with special care to ensure that component operation and stress remain normal in all regards despite the usage rate. For instance, a high usage rate can result in an increase of component temperature that usually reduces the cycles to failure, can activate other failure modes or delay degradation of components sensitive to thermal cycling. Care should be taken to control the critical design variables (e.g. by cooling) to avoid over stresses.

Time acceleration can thus be performed by applying the load at a higher frequency. In that case it is important that the amplitude response of the structure does not change due to the change of input frequencies. Therefore, it is mostly applicable in component testing. Another kind of time acceleration is to remove segments of the signal that induce negligible damage, see e.g. [8]; Sec. 4.3.3. This technique is often used for verification on the system level, since it does not change the frequency of the remaining signal.

4.3.2 Cycle Acceleration

In most cases of material fatigue, the time scale of the mechanical stress has no or negligible impact on the fatigue life, only the sequence and values of the turning points of the load are of importance. Therefore, the sequence of turning points can be reproduced at a higher rate than normal usage. Further, load cycles that have negligible contribution to the fatigue damage can be omitted in the test. In fatigue testing, small amplitude cycles that cause negligible damage can be removed by using the so-called rainflow cycle filter, for details see e.g. [8]; Sec. 4.3.1. This is an efficient way of reducing the length of the load signal, without significantly affecting its fatigue damage content. However, the frequency information of the signal is lost, and the method is therefore usually only applicable in component testing.

4.3.3 Overstress Testing

Amplitude acceleration or overstress testing is one of the most common forms of accelerated testing. It consists of running a test at higher-than-normal levels of some load variables to shorten its life or to degrade its performance faster. Typical accelerating loads are temperature, voltage, mechanical load, thermal cycling, humidity and vibration. Amplitude acceleration, by for example, multiplying the signal by a scale factor is an efficient way of making the load more severe, while keeping the frequency content. However, it should be used with care since the increased load levels may change the failure mechanism. Further, the degree of acceleration depends on the increase of damage due to the increased load levels. Consequently, a damage model needs to be used in order to estimate the acceleration factor. Different methods for overstress testing are presented in Section 4.4.

4.3.4 Environment Acceleration

Environment acceleration involves performing tests at more severe environments than normal can be an efficient acceleration method, and can be achieved e.g. by elevated temperature, higher pressure, increased friction, severe corrosive environment or influence of bio fouling. However, as for amplitude acceleration, care is needed since the failure mechanism may change when applying a too severe environmental acceleration. The acceleration factors achieved by the environment typically needs to be assessed by physical or empirical models. An example can be dynamic seals where higher pressure, temperature and friction implies reduced life, see e.g. [40].

4.3.5 Resistance Degradation

Acceleration can also be performed by weakening the component and thus reducing the resistance or strength of the component. Life of some products can be reduced by modifying the size, geometry and finish of components. Engineering design variables affect component life (e.g., insulation thickness). Besides, geometry may affect component life (e.g. notches produce local high stress and early failure). Finally, surface finish (roughness) and residual stresses of metal components affect fatigue life.

4.4 Overstress Testing Methods

One of the main premises for accelerated reliability testing is that increasing a source of stress will decrease the average time-to-failure and the variability of the time-to-failure [39]. By measuring the time-to-failure at different levels of loading, the relationship between the time-to-failure and the load level can be determined. Overstress testing is especially relevant for testing of electrical components, and the methods will here be presented in an increasing complexity of the loading.

- **Constant loading**. Such testing is simple and has many advantages. In most tests, it is easier to maintain a constant load level. Accelerated test models for constant loading are better developed and empirically verified for some materials and components. Besides, data analyses for reliability estimation are well developed. The main drawback is that there is little established theory for using constant loading results to estimate component life under varying loading. Constant loading should then be used for testing components that operate in quasi-steady conditions during its lifetime.

- **Step loading**. This method subjects a fixed number of components to progressively higher load levels. A constant loading is applied to the component for a specified length of time. If it does not fail, the loading is increased in steps until it fails. Usually, all components tested go through the same pattern of load levels and test times. The main advantage of a step loading test is that it rapidly yields failures. A drawback is that failure modes occurring at high load levels (i.e. in later steps) may differ from those at use conditions. To avoid this, load levels should not be so high as to produce other failure modes that rarely occur at the design loads. The precision of the test depends on the number of components tested, the fraction of components that pass the test and how loads are increased. It must be taken into account that at low load levels, the time to failure can be very long and therefore also the times to failure. If the loads are increased in a way that biases the test toward one failure mode, then the time-to-failure results will be inherently inaccurate.

- **Progressive loading**. This method is essentially a variation of the step loading testing. In progressive loading testing, a component undergoes a continuously increasing level of loading. Different groups of components may undergo different progressive load patterns. Progressive loading tests have the same disadvantages as step loading tests. Moreover, it may be difficult to control the progressive loading accurately enough.

- **Cyclic loading**. It is quite common that components repeatedly undergo a cyclic loading in actual operation. For example, insulation under AC voltage experience a sinusoidal stress. A cyclic loading test for such a product repeatedly loads the component with the same pattern of loads. For the purposes of modelling and data analysis, the load level (i.e. amplitude) is regarded as a constant. The frequency and length of a cycle may affect life and, if relevant, they should be also included in the degradation model as variables.

- **Random loading**. WEC components in use commonly endure varying changing levels of loading. Then an accelerated test typically uses random loading with the same distribution as actual random loads but at higher levels. Like cyclic loading tests, random loading models should employ some characteristics of the load distribution (i.e. mean, standard deviation, correlation function, and power spectral density).

Table 16 summarises the advantages and disadvantages of the different overstress testing methods described above.

Table 16: Advantages and limitations for the main overstress testing methods.

Method	Advantages	Limitations
Constant loading	• Simplicity • Test models for constant loads are better developed and empirically verified • Data analyses for reliability estimation are well developed	• Little established theory for using constant loading results to estimate component life under varying loading
Step loading	• Rapidly yields failures • Highly repeatable	• High load levels may activate different failure modes and yield inaccurate time to failure results.
Progressive loading	• Different groups of components may undergo different progressive loading patterns	• Same disadvantages as step loading tests • Difficult to control the progressive stress accurately enough
Cyclic loading	• Harmonic loads are easy to produce	• The frequency and length of a cycle may affect life and, if relevant, they should be also included in the degradation model
Random loading	• WECs are tested under varying loading in actual use	• Same distribution as actual random loading must be used

4.5 Accelerated Testing Examples from Other Industries

While the general aim of accelerated testing is clear (i.e. to gain information on component life or performance in a reduced amount of time, as previously mentioned in Section 1.2.3), a variety of approaches are applied in different industries in order to achieve this target. Some examples, taken from different industrial sectors, are reported in the following subsections.

4.5.1 Evaluation of Fatigue Life

A typical example of the need to determine failure conditions in a shorter time compared to real service conditions is related to the fatigue of materials and components. A component or a structure can be subjected to a load cyclically during its life and there is the need to get a response on the projected fatigue life performance in a shorter time. In this sense, Stress vs Number of cycles (S-N) curves have been derived based on a series of experimental tests performed at different stress levels corresponding to different number of cycles. Such curves, available for different classes of materials and structural details and for different service environment (i.e. air, sea water with or without cathodic protection) are used in standards for design purpose or to verify fatigue performance compared to a specified design curve, see e.g. [41], [42].

In the case of experimental verification, accelerated tests can be performed on a simple specimen, or on a more complex shape component, to test material fatigue performance. To simulate the effect of a cyclic loading corresponding to the application of a load for a defined number of years, tests are performed repeating a load cycle for the number of times representative of a period of time (e.g. design life or service life) at a frequency higher than the one experienced by the material or component during service. Sometimes tests at resonance frequency are performed, in particular for materials used in aerospace application.

Moreover, the concept of damage equivalent load is also used, allowing the conversion of design loads acting on the component/structure into an equivalent damage load, constant amplitude load and load ratio that can be reproduced by experimental tests for a shorter test duration. This approach is used for example in wind turbines for which a typical load spectrum can consist of more than 500 million load cycles occurring at a wide range of load ratios. In this case, the test of a component (e.g. a blade) for such a long number of cycles is not possible as the test duration would be not reasonable. Through the damage equivalent approach (i.e. Miner's Rule approach) it is possible to accelerate the level of damage for each load cycle so to obtain the damage equivalent in a significantly reduced time period.

4.5.2 Qualification of Connections for Oil & Gas Wells

A different approach can be observed for the case of *Oil & Gas wells*. The tubular conduits that convey the fluid from the reservoir to the ground are several km long and are made by steel/high alloy pipes about 10m long, joined by means of special connections. These connections are required to guarantee structural integrity and sealing capability and maintain this performance for the life of the well, that is typically in the order of 20 years. The approach adopted to assure this performance is to carry out a series of full-scale testing on samples of connections, manufactured to worst-case extremes of dimensional tolerances and subject in dedicated testing laboratories to a combination of different loads that can be experienced by the connections (tension/compression, bending, internal/external pressure, temperature cycles). The loads are applied to the maximum possible levels of either the foreseen connection performance or the full capacity of the pipes, accounting for real dimensions and mechanical properties. Failure tests are carried out at the end of the testing sequence to evaluate the structural resistance. In this way, the performance envelope of the connection as established by the manufacturer is verified. The test program duration may vary between two and four weeks for each specimen, for a maximum of five specimens for a complete qualification program. By performing this repeated testing sequence with successful results, objective evidence is provided that the connections design is conform to its stated performance envelope for the specific combination of size and material tested. International standards are in place (e.g. [43], [44]) to guide the evaluation process.

4.5.3 Determination of Corrosion Resistance

Accelerated tests are used in the determination of corrosion resistance in many applications, for instance Oil & gas, marine and offshore applications.

To carry out material selection at the design stage, as well as to define properly the reliability and maintenance of the structure, it is crucial to know the damage mechanisms and the corrosion rates in the defined environment that will allow the prediction of the behaviour of materials and components over a long-term period. This is possible through experimental tests that consist of the exposure of materials in a defined environment under a loading condition more severe than what the component can experience during service in the same period. As an example, referring to material selection, there are tests allowing to establish if a material is suitable or not to work in a selected environment. For example, the dead weight test and four point test in oil and gas applications (e.g. [45], [46]) allows the resistance of materials against sulphide stress cracking and stress corrosion cracking to be determined, in addition to screening the performance of metals in a specific environment for an accelerated time.

Slow strain rate tests can be considered as another example of accelerated test. The test consists of a tensile test performed at slow strain rate and reproducing the environment of interest. This test is used to assess the resistance of materials to a specific environment and can provide information about the resistance of materials in a specific environment. In oil & gas applications it is used to determine the resistance of materials against hydrogen embrittlement and has been also used in nuclear and aeronautical industries to determine the materials stress corrosion cracking (SCC) susceptibility or to perform a ranking between different alloys.

4.5.4 Vibrational Resistance

The problem of assuring the safety and integrity of the shipments is one of the most important for the shipping industry. The shipping units, with their interior packing and means of closure, have to withstand an extremely variable range of usage conditions. There are four basic modes of transport (road, rail, air, and ocean) and within each mode there can be a number of variables, such as types and sub-types of vehicles, lading amount and configuration, transit conditions (highway, track, turbulence, sea state), etc. It is unrealistic to think that a single or simple test could simulate all these different combinations. A widely accepted approach is to perform random vibration tests. A vibration table moves with a constantly changing complex mixture of frequencies and amplitudes, generally similar to the way transport vehicles actually move. As a result, these tests can nearly simulate actual field and transport conditions. Random vibration is typically described by power spectral density (PSD), describing an "average" acceleration intensity in the frequency domain. Standards like [47] or [48] describe how to perform these tests and define general purpose PSDs for different types of transport systems.

4.5.5 Extending the Design Life of Components for Nuclear Industry

A need is emerging in the nuclear power industry to extend the service life of nuclear reactors to 60 years. Future nuclear reactors (GEN IV) will operate in a low-carbon energy system with a large share of renewables with intermittent energy production and nuclear reactors will need to balance this by either operating in a load-following mode, which would increase the number of load cycles significantly, or operate in a baseload mode and store the excess energy. An important strategy for the future is to design components so they can be inspected, repaired and replaced if necessary. Some components are, however, non-replaceable, or only replaceable at very high cost, and should be designed for more than a 60 years life. Today's design codes are based on 40 years' service-life under essentially baseload operation. Extending the service-life to 60 years will require new material models for materials characteristics like thermal ageing, creep, creep-fatigue or long-term low dose irradiation. To achieve this goal, the development of adequate methodologies to predict long-term degradation from accelerated tests is of paramount importance. Extensive research is in progress, at national and European level[11] to cope with this problem, that is still open.

4.6 Standards and Guidelines for Component Design and Testing for WEC Technologies

A desktop study to identify the general best practices and standards related to WEC technologies has been performed in Task 1.1. There are few documents that provide information about design or testing of WECs, however the International Electrotechnical Commission (IEC) technical committee TC114 [49] is developing a set of standards for the Marine Energy sector, the **IEC 62600 series**, "*Marine Energy - Wave, Tidal and Other Water Current Converters*". A comprehensive set of documents is being developed, covering different aspects and the various types of marine energy devices, as shown in Figure 26.

The scope of this standardization effort is to accelerate the development of standards and certification schemes for marine energy technologies under the umbrella of the IEC, in order to facilitate international trade and acceptance of industrial devices and products. A first group of 'generic' documents covers general aspects common to the various types of MEC, including design requirements to ensure the engineering integrity of marine energy converters.

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[11] http://www.eera-jpnm.eu/?q=jpnm&sq=suba

It is important to follow a design path that will minimize the risks encountered along a technically complex route. The **IEC 62600-2** Technical Specification (TS) [38] presents a guide that addresses these issues, the approach being based on a proven methodology adapted from other technology areas. A part of the standard series is also related to scale testing (**IEC 62600-103**, [3]), which aims to physically simulate realistic scenarios in a controlled environment, intended as a way to accelerate the development with appropriate testing methods without being subject, at an early development phase, to the difficulties related with full-scale testing of novel concepts and/or devices.

The structured development schedule presented in **IEC 62600-103** makes use of the ability to accurately scale WECs such that experimental models can be used to investigate the relevant device parameters and design variables at an appropriate dimension and associated budget. Experimental testing may also complement numerical modelling activities by e.g. providing suitable sources of validation data. Accelerated testing in a hybrid environment, where both numerical and experimental models are used, can become an attractive approach, especially at low to medium TRLs. In this way, it could be possible to get relevant information on structural and operational issues to support design at an early development stage.

Further information on scaling considerations for WEC testing will be presented in VALID Deliverable D1.2 "*Critical Components and Modelling Limitations*".

Generic	Wave	Tidal	Rivers	OTEC
-1 Terminology	-100 Performance	-200 Performance	-300 Performance	-20 OTEC Design Assessment
-2 Design Requirements	-101 Resource	-201 Resource	-301 Resource	
-10 Moorings	-102 2nd Location	-202 Scale Testing		
-30 Power Quality	-103 Scale Testing			
-40 Acoustic Measurement				
-3 Loads Measurement				
-4 Technology Qualification				

Figure 26: Overview of IEC TC 114 62600 series of standards for marine and water current energy converters [49]

In [16], a review of guidelines and standards for the design of WECs is given. The review presented in [16] has been used as a starting point to make an initial overview of the most relevant best practices and standards. An overview of the standards and guidelines identified is presented in Table 17 and Table 18.

Table 17 Overview of WEC design standards and guidelines

DNV "Guidelines on Design and Operation of Wave Energy Converters", May 2005, The Carbon Trust [50]
This guideline provides an indication of the application of existing codes and standards to WEC devices, relying on regulations available from offshore and maritime industries as environmental loads and technical challenges experienced by WEC are considered quite similar to those applications. A list of related guidelines and standards is made available. The guideline provides information about the qualification process, failure mode identification and risk ranking, risk analysis and outline design criteria for structures and foundation. Moreover, the document describes methodologies for fatigue analysis, and waves and loads modelling. Concerning testing processes a highlight is given about the importance of properly identify and understand the failure modes. In the document accelerated tests are not mentioned. Reference is made to fatigue tests to prove the S-N curve adopted in a design process, in case a higher curve than the one suggested in the relevant standard (e.g. [42]) is selected. Model tests are mentioned as a support for the calculation of hydrodynamic response.
DNV-OSS-312 Certification of Tidal and Wave Energy Converters, October 2008 [51]
This specification is based on the experience gained in the oil and gas industry duly adapted to the safety levels needed for renewable energy installations. The document presents principles and procedures related to certification of tidal and wave energy converters, providing an overview of needed documentation. The document refers to testing as a support element to the analytical approach in handling the uncertainties in the technology. Testing is mentioned at different levels of development, from basic testing on materials to focus on material properties and degradation mechanisms to prototype test, Factory Acceptance Test (FAT) up to pilot test. Table 3 of [51] presents recommended tests for systems and components. Functional testing is also mentioned to be carried out if deemed necessary. No technical provisions are included in the document.
EMEC "Guidelines for Design Basis of Marine Energy Conversion Systems", 2009 [52]
This guideline provides step-by-step guidance for a WEC device developer to understand the factors influencing the design of marine energy conversion systems. The document covers wave and tidal energy converters. It is assumed that general layout and operational functions have been already determined that numerical and physical modelling tests (scaled and/or full-size prototypes) have been conducted and performance assessments have been already undertaken.
IEA-OES "An International Evaluation And Guidance Framework For Ocean Energy Technology", 2021 [10]
This document is an output of IEA-OES Task 12, an activity funded by the members of the International Energy Agency (IEA) Ocean Energy Systems (OES) Technology Collaboration Programme (TCP). The scope of this document includes technology associated with utility-scale electricity generation from ocean waves and tidal streams. Future Task 12 activity will expand to incorporate other forms of ocean energy. Electricity is likely to be the main output ocean energy technologies; however, it is recognised that alternative markets are emerging where other functionality may be desirable. Most of the guidance presented in this report are still valid for such alternative

applications, but may require case by case adaption, e.g. for situations where electricity is not the primary output.

The objectives of Task 12 are:

- Build international consensus on ocean energy technology evaluation
- Guide appropriate and robust activities throughout the technology development process
- Share knowledge and promote collaboration
- Support decision making associated with technology evaluation and funding allocation

This document intends to support international efforts by presenting a framework for technology evaluation and guidance of engineering activity, ensuring that decision-makers have consistent information available to them.

The designer of a WEC can also take advantage of the similarity with structures used in different offshore applications, such as oil & gas, maritime and offshore wind. In fact, there are a number of standards that can be used as a support in the design and qualification of WECs. Table 18 presents examples of relevant standards and guidelines from other offshore industries.

Table 18 Examples of relevant standards and guidelines from other offshore industries

GL Rules and Guidelines IV-6-4 (2007) Rules for Classification and Construction IV Industrial Services [53]	This guideline provides a description of environmental conditions (e.g. wind, sea current and waves), design loads and principles for structural design. The guideline refers to model tests as a tool to validate specific aspects related to wave loads (e.g. the influence of damping) and to fatigue issues (e.g. stress concentration factors, classification of details). Testing is also considered for steel or concrete structures (e.g. material requirements) and structural interfaces, e.g. welding procedures and details.
GL Rules and Guidelines IV-2-5 (2012) Guideline for the Certification of Offshore Wind Turbines - Strength Analyses [54]	This guideline applies to the design, assessment and certification of offshore wind turbines and offshore wind farms, principally structural design and strength analysis. Section 10 of the guideline refers to testing of offshore wind turbines at prototype level.
DNVGL-ST-0119 (2018) Floating Wind Turbine Structures [55]	This standard addresses the structural design of floating wind turbine structures providing design principles and overall requirements. The standard foresees design assisted by the testing approach, through testing of the actual performance of full-scale structures to determine load effects, structural resistance and material degradation.
ISO 19902 Petroleum and natural gas industries: Fixed Steel Offshore Structures [56]	This standard provides requirements and recommendations applicable to fixed steel offshore structures for the petroleum and natural gas industries, such as bottom founded structures, steel gravity structures or jack-ups.
API RP 2A-WSD 22nd Ed. (2014) Planning, Designing, and Constructing Fixed Offshore	This recommended practice relates to the design and construction of new fixed platform and relocation of existing platforms.

Platforms - Working Stress Design [57]	
API RP 2A-LRFD (2019) Planning, Designing, and Constructing Fixed Offshore Platforms - Load and Resistance Factor Design [58]	This recommended practice provides requirements and recommendations for fixed offshore structures for petroleum and natural gas industries, jacket, and towers but is it is applicable also to other structures related to offshore structures.
DNV-RP-F205 (2010) Global Performance Analysis of Deepwater Floating Structures Plan Approval Document Types [59]	This document provides guidance on coupled analysis for deep-water floating structures.

Finally several standards are available addressing fatigue design and assessment in fields related to WEC application, such as [60]**,** [41] and [42]. In particular, [42] presents a dedicated section where the possibility to introduce the qualification of new S-N curves based on fatigue test data is presented. Suggestions about testing and methodology to extrapolate the relevant S-N curve are provided.

The standards assessment will be further developed in VALID WP6 "*Overall Assessment and Standardisation*" that will focus on the analysis of existing standards and regulations starting from the information provided in this document and identifying areas of improvement in existing technical specifications, to liaise with IEC technical committees and provide targeted test results and guidelines towards the development of future standards.

5 FMECA: Critical Sub-Systems and Components

The three user cases introduced in Section 3.3 have performed an analysis with the aim of identifying relevant critical sub-systems and components in their WEC designs. User-cases provided their relevant FMECA worksheet to RINA-C, whom subsequently reviewed each of them and summarised the critical Sub-systems and components identified by the User-cases in the following sections.

In particular, the FMECA, described in Section 3.1.3.1, is an appropriate tool to investigate criticalities at any system level thanks to its systematic sorting of all the constituent element of a system and the possibility to applicate it in every project phase. It has to be highlighted the necessity to evaluate at what level of complexity the information regarding the probability of occurrence and the effects on the system are available.

It is fundamental to identify all conceivable failure modes of each item and to clearly define which is the reference Risk Matrix (see Section 3.1.3.1).

5.1 User Case #1: CorPower

CorPower developed a very detailed FMECA in which, in addition to the fields described in the general methodology (please refer to Section 3.1.3.1), the failure causes are investigated, and detailed improvement actions are suggested by area of intervention (Mechanical, Electrical, Control and Detection). The risk is then re-evaluated by CorPower after improvement actions are implemented, as per Figure 27.

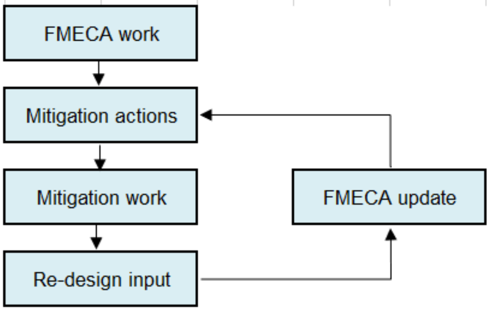

Figure 27: CorPower risk evaluation process

The CorPower analysis considers dry testing and operation phases.

The following criticalities have been identified by CorPower:

- Module M01 Pretension System seals and rod have been identified as high-risk components. The pre-tension system provides a downward force on the buoy, replacing the mass that would otherwise be needed to balance the buoyancy at midpoint. The failure of the seals would give a leakage and a successive structural failure of the rod, resulting in the loss of the pretension function of the device, which in turn could lead to the loss of the WEC in the worst-case scenario. Potential causes of a seal failure could be fatigue, degradation or corrosion of the rod, and/or wear, degradation, lack of lubrication and high temperature on the sealing box, and/or rod surface damage. The failure of the sealing box is identified through a sensor, while for the rod and seals it is achieved through data analysis. To mitigate the risks connected to the sealing box, seal rig testing and pressure tests have been performed. For the risk connected to the seals, the mitigation measures are seal rig testing, Hardware-in-Loop test rig testing (fully assembled PTO running in the test-rig for dry testing) and, in some cases, usage of standard seals. Mitigation actions for the rod include design according to standards, increased margin on life, avoiding welding, buckling analysis (safety margins), pressure measurements, loads recorded during operation and compared to design, and pressure testing. These measures allowed to reduce the risk level from high to medium.

- In the Module M02 WaveSpring, seals have been identified as medium-to-high-risk components. WaveSpring is a phase control technology that allows to amplify the WEC motion with the waves. A leakage failure would result in lost or reduced function of the WaveSpring and lead to reduced power output of the WEC. Such failures are detected by sensors and are caused by wear, contamination of air and lack of lubrication. The mitigation measures include extensive testing in the seal rig with results feeding into the design and allowed to reduce the risks from medium-to-high to medium.
- In the Module M12 PTO Frame, ocean rods and rod guiding seal glands have been identified as medium-risk components. The failures on ocean rods can be a structural failure or surface damage, resulting in loss of module function and potential loss of WEC, or water ingress. The structural failure can be caused by overload, corrosion and rod coating degradation. The surface damage can be caused by overload, biofouling, corrosion and rod coating degradation. The seal glands may suffer leakage, caused by wear or overload, which may lead to water ingress into the system. All these failures are detected by data analysis. Mitigation of the structural failure of the rods includes laser cladding, design reviews and safety factors. Mitigation actions for the surface damage are biofouling testing and seal rig testing. The risk related to the seal glands are also mitigated through the seal rig testing. The risk of surface damage failure on the rod and the leakage risk on the seal gland have thus been reduced to low.
- In the Module M12 WEC Hull (the buoy), seals have been identified as medium-risk components due to potential leakage, which can cause water ingress and thus shutdown of WEC and compromised stability. Such failure is detected by water sensors from bilge system. To mitigate the risk double seals will be used and pressure testing performed before deployment. The risk stays unchanged at medium level, however testing at each deployment is intended in order to minimize the risk.

Between all the criticalities mentioned in the above, CorPower will pay specific attention on the testing of dynamic sealing failure in WP3.

5.2 User Case #2: IDOM

IDOM's FMECA is developed in an iterative process, so the risk level is calculated, mitigation measure is suggested, and the risk is re-evaluated after implementation of the mitigation action.

Ten risks have been identified by IDOM for the PTO system:

- One is related to the generator rotor shat bearing.
- Four are related to the rotor.
- One is related to the valve protecting the generator.
- Two are related to the valve actuator.
- Two are related to the generator.

Two of these risks are directly related to the VALID project.

The first risk is the rotor - generator shaft bearings failure. The shafts are undergoing cyclic loads, accelerations and gyroscopic effects due the WEC movement, and in a marine environment, leading to a fast degradation.

The mitigation measure identified is to design for extreme conditions (accelerations) and define acceptance criteria.

The second risk is the generator overheating during the power peaks generation. For a sea state, the air flux produced in an OWC air chamber is oscillating leading to an oscillating generated energy transmitted to the generator. Furthermore, sea state conditions are very variable. Selecting a nominal power based on the peak for the most energetic sea state leads to an over-dimensioned generator for the most sea states and most part of the cycles. The fixed energy losses, which increased with the generator size, would be large.

IDOM's strategy to reduce these losses consists in that the generator nominal power is less than the peak power during some time instants. Although these peaks last few seconds, the generator works above its design conditions leading to overheating, accelerating the generator degradation.

The mitigation measures identified are:

1. Include in specification temperature sensors
2. Use reinforced insulation
3. Study overheating from power peaks

By the implementation of the mitigation actions the risk is reduced to low for both the criticalities identified.

In WP4, IDOM analysis will be focused on the PTO and, specifically, on the failure of the electric generator. The user case will better define the FMECA, all the input data and the relevant environmental factors influencing it.

5.3 User Case #3: Wavepiston

The analysis provided by Wavepiston at this stage is a preliminary FMECA.

In this analysis the system is analysed at a higher level; subsystems are analysed in the different lifecycles (e.g. Design, installation, operation…), but they are not always subdivided in constituent element and therefore failure modes are not clearly identified.

The preliminary analysis carried out by Wavepiston identified 66 criticalities, but it is not clear which is the critically level since the risk matrix is not provided and the likelihood and consequences ranking are not indicated in the worksheet.

The preliminary FMECA produced by Wavepiston is at very high level since their project is at a preliminary stage and, consequently, it has not been possible to perform an analysis at the same level of detail of the other User Cases. Once the project will be at sufficient stage of development, the FMECA could be developed in detail and the results could be critically analysed. Such analysis will be carried out in WP5, where the failure of the hydraulic pump will be the main criticality considered.

6 Summary of the Key Findings and Proposed Next Steps

This report is focused on the description of the different typologies of WECs currently available and on the identification of the main potential criticalities, in terms of reliability and survivability, that may occur at a sub-system or component level.

As reported in Section 3.1.2, the marine environment is challenging for the operation of machinery (e.g. corrosive, discontinue fatigue cycles, quick condition changing, etc.) and the collapsing of one or more WEC sub-systems could be crucial for the survivability of the entire WEC. For this reason, it is highly advised that key WEC sub-systems / components undergo intensive studies and dedicated tests prior to full-scale ocean deployment, to predict and prevent failure(s).

According to the findings of this task, the most critical components of a WEC are related to the PTO, to the mooring sub-systems, and to auxiliary components such as seals, power electronic equipment and, where applicable, other mechanical moving parts. Furthermore, it is important to underline that the term criticality means the total or partial failure of a component.

The methodologies applied in VALID Task 1.1 to identify critical sub-systems and components included:

- Literature Review based on the analysis and the review of available papers and reports (Section 3.1).
- Industry Survey, a questionnaire with appropriate questions forwarded to technology developers and experts within the WEC sector, both internal and external to the VALID consortium (Section 3.2).
- Feedback from the User Cases with a description of their methodology (e.g. FMECA, FMEA) to assess potential criticalities of their WEC technologies (Section 3.3 and Section 5).

Table 19 reports the WEC components and sub-systems that have been identified in VALID Task 1.1 as *critical* through the different methodologies mentioned above. Some of the sub-systems and components emerged as critical through all the studies carried out (i.e. literature review, industry survey, User Cases' FMECA analysis) and can therefore be considered of particular interest to the VALID. The other components listed emerged only from one or two of the studies conducted but should still be considered to be of interest to VALID and the wider wave energy sector.

As highlighted in Table 19, the PTO sub-system was considered critical from all the different sources. The mooring sub-system was considered critical from the literature review and the industry survey, but it did not emerge as a priority from the VALID User Case FMECAs. The survey also highlighted the hydrodynamic sub-system as a potential critical path to failure.

A number of additional criticalities were also identified by the VALID User Cases at component level, in particular:

- Components at the interface of different sub-systems, such as seals.
- Key sub-system components, e.g. valves and hydraulic cylinders.

Table 19: VALID ranking of sub-systems and components

Critical Component / sub-system	Criticality identified from the literature review	Criticality identified from the survey	Criticality identified from the User Case FMECA analysis
Energy Conversion			
PTO sub-system	X	X	X
Electric generator	X		X
Rotor	X		X
Power electronic equipment	X		
Marine Interface			
Mooring sub-system	X	X	
Hydrodynamic system		X	
Auxiliary Components			
Rod (actuators)	X		X
Bearings	X		
Valves	X		X
Seals			X

In Section 4, an introduction to different types of accelerated testing and relevant acceleration testing methods was provided, as well as a general overview of the main guidelines and standards for both the design and testing phase available for WEC technology and for the related industries. Key definitions and an outline of the requirements for accelerated tests have also been reported in Section 4.3. The acceleration methods described include time, cycle, overstress and environment acceleration, along with resistance degradation.

From a preliminary analysis, it is clear that the different accelerated tests can be considered to target different testing objectives (e.g. material corrosion, material endurance, resistance of mechanical parts, resistance of sealings, etc). The types of accelerated tests described in this report can be mostly dedicated to a set of WEC sub-systems/components. In this way, the technology developer can choose a proper test according to the test objectives.

Overall, it is considered that time acceleration (high usage rate) and overstress testing represents the most intuitive tests to be applied to WECs, while the other reported accelerating methods need a detailed background preparation and computing capacity. It is important to underline that while overstress method represents one of the most user-friendly tests, it needs an optimum setup of main tests parameters: for example, increasing too much working condition may affect the physics of a failure, and then totally mispresent results. The same argument can be applied to the other most common accelerating test, the high usage rate test (i.e. the high usage rate applied to a sub-system could produce failure modes that cannot be seen at normal usage rate).

Considering that the WEC industry is at an early development stage, all the reported accelerated tests will still have a strong empirical component that limits the diffusion of precise guidelines and normative. In addition, at present, there is a limited number of standard and guidelines available for the design and the testing of WEC devices. The development of such documents is ongoing and will be further investigated in VALID WP6 "*Overall Assessment and Standardisation*".

The identified critical sub-systems and components shall be addressed and analysed in the following work packages VALID:

- WP3 – User Case #1: Testing of Dynamic Sealing Failure.
- WP4 – User Case #2: Testing of Electric Generator Failure.
- WP5 – User Case #3: Testing of Hydraulic Pump Failure.

Finally, this first deliverable also provides guidance for Deliverable 1.2 “*Modelling Approaches and Associated Limitations*” and Deliverable 2.1 “*Requirements for the VALID Test Platform*”.

Nomenclature

Abbreviations

ALS	Accident Limit State
AWS	Archimedes Wave Swing
BFD	Block Functionality Diagram
CAPEX	Capital Expenditure
CI	Criticality Index
DFF	Design Fatigue Factor
DFMECA	Design Failure Mode and Effect Analysis
DLC	Design Load Case
EC	European Commission
EMEC	European Marine Energy Centre
ETA	Event Tree Analysis
EU	European Union
FAT	Factory Acceptance Test
FLS	Fatigue Limit State
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FTA	Fault Tree Analysis
GDPR	General Data Protection Regulation
HALT	Highly Accelerated Life Test
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability study
H2020	Horizon 2020
IEC	International Electrotechnical Commission
MEC	Marine Energy Converters
OPERA	Operational Problem Analysis
OPEX	Operating Expenditure
OWC	Oscillating Water Column
OWE	Oceanic Wave
OWSC	Oscillating Wave Surge Converter
P&ID	Piping & Instrumentation Diagrams
PFD	Process Flow Diagrams
PSD	Power Spectral Density
PTO	Power Take-Off
RES	Renewable Energy Source

RI	Reference Items
RMS	Root-Mean-Square
SDWED	Structural Design of Wave Energy Devices
SCC	Stress Corrosion Cracking
SWIFT	Structured What-if checklist
TRL	Technology Readiness Level
TS	Technical Specification
ULS	Ultimate Limit State
VMEA	Variation Mode and Effect Analysis
WD	Wave Dragon
WEC	Wave Energy Converter
WP	Work Package

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[57] *API RP 2A-WSD 22ND ED: Planning, Designing, and Constructing Fixed Offshore Platforms - Working Stress Design*, 22nd ed. API, 2014.
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[59] 'DNV-RP-F205: Global Performance Analysis of Deepwater Floating Structures', *DNV*, Oct. 2010.
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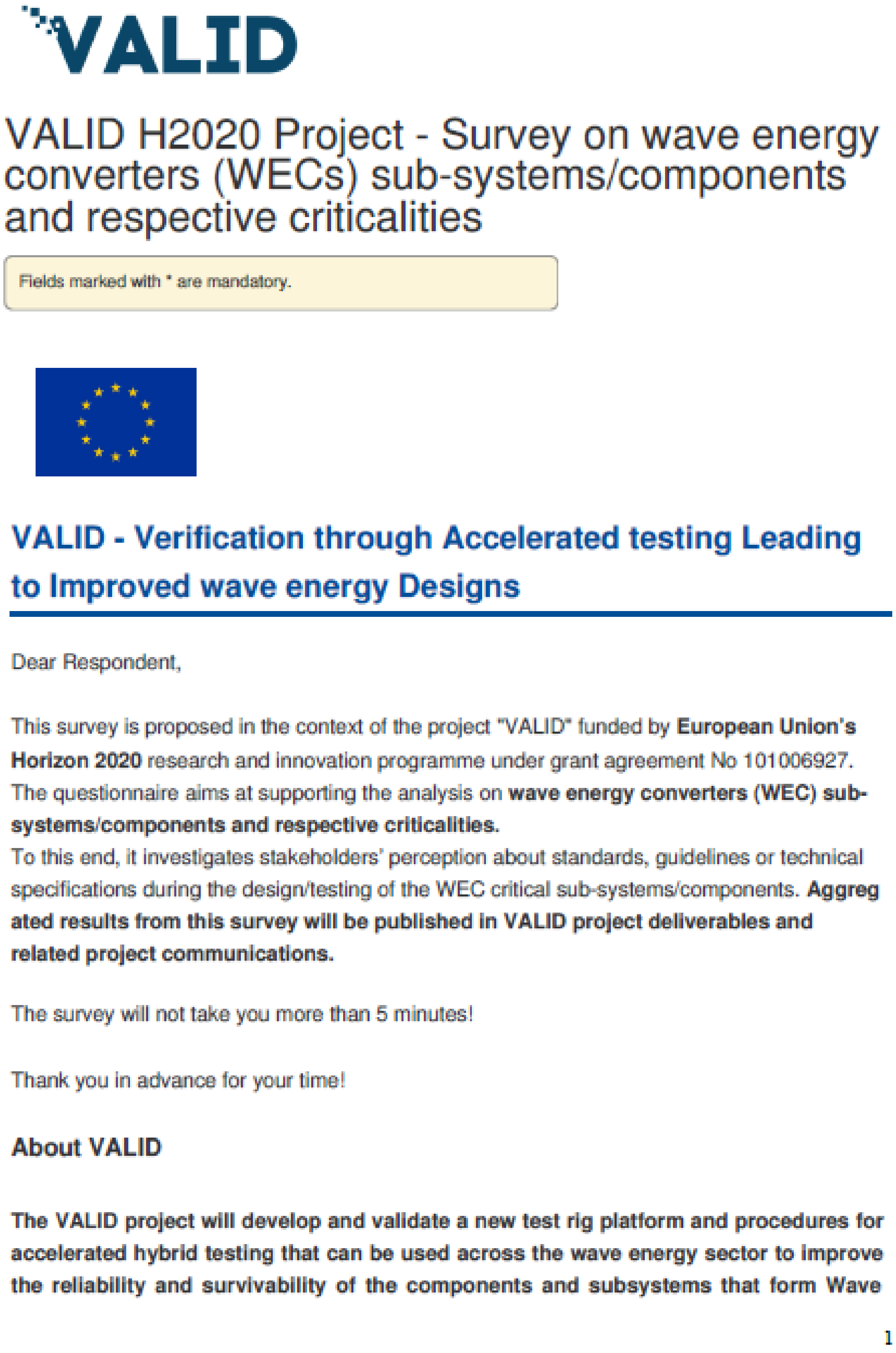
Annex A: Survey Example



VALID H2020 Project - Survey on wave energy converters (WECs) sub-systems/components and respective criticalities

Fields marked with * are mandatory.

VALID - Verification through Accelerated testing Leading to Improved wave energy Designs

Dear Respondent,

This survey is proposed in the context of the project "VALID" funded by **European Union's Horizon 2020** research and innovation programme under grant agreement No 101006927. The questionnaire aims at supporting the analysis on **wave energy converters (WEC) sub-systems/components and respective criticalities.**
To this end, it investigates stakeholders' perception about standards, guidelines or technical specifications during the design/testing of the WEC critical sub-systems/components. **Aggregated results from this survey will be published in VALID project deliverables and related project communications.**

The survey will not take you more than 5 minutes!

Thank you in advance for your time!

About VALID

The VALID project will develop and validate a new test rig platform and procedures for accelerated hybrid testing that can be used across the wave energy sector to improve the reliability and survivability of the components and subsystems that form Wave

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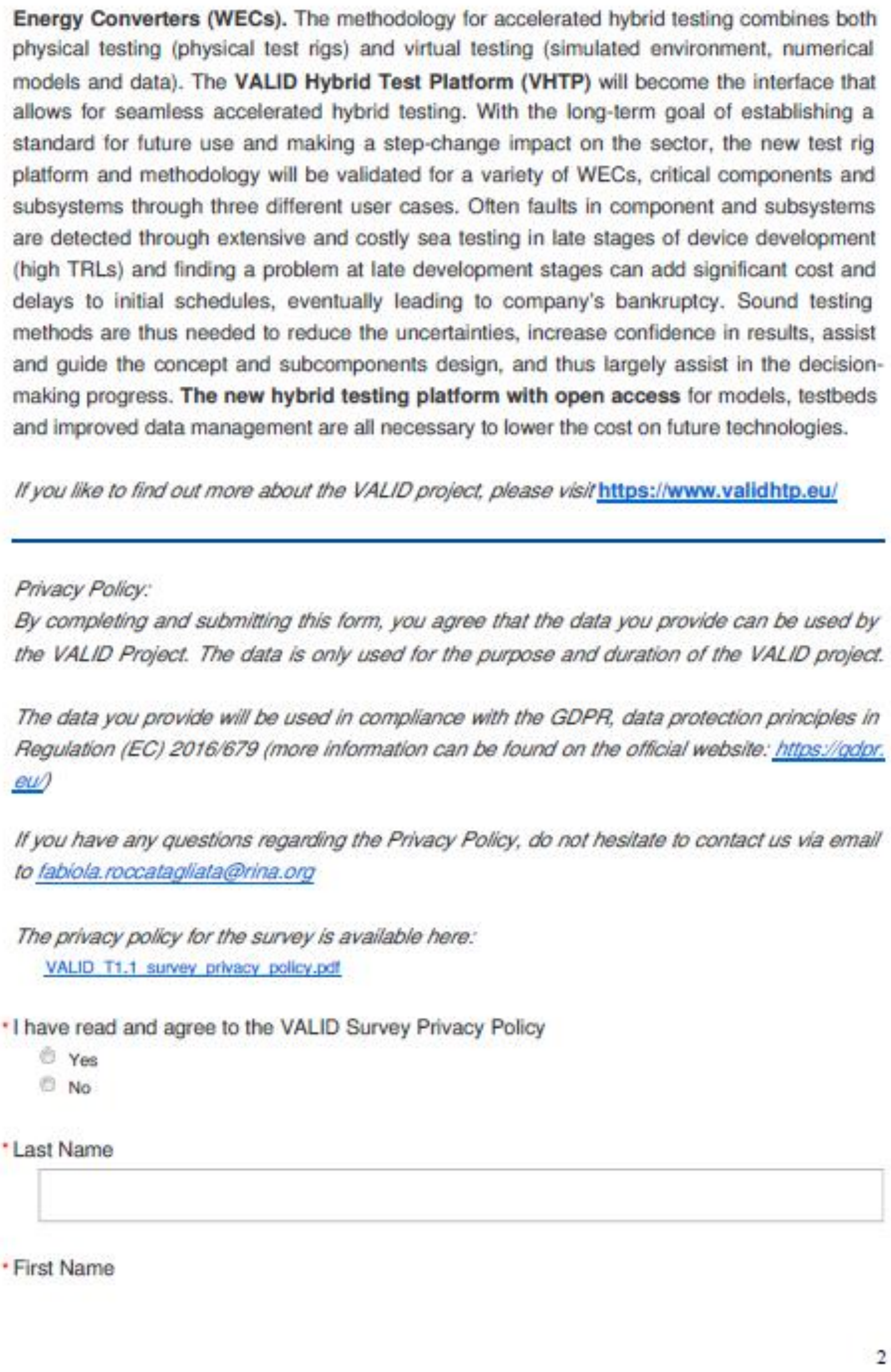


Energy Converters (WECs). The methodology for accelerated hybrid testing combines both physical testing (physical test rigs) and virtual testing (simulated environment, numerical models and data). The **VALID Hybrid Test Platform (VHTP)** will become the interface that allows for seamless accelerated hybrid testing. With the long-term goal of establishing a standard for future use and making a step-change impact on the sector, the new test rig platform and methodology will be validated for a variety of WECs, critical components and subsystems through three different user cases. Often faults in component and subsystems are detected through extensive and costly sea testing in late stages of device development (high TRLs) and finding a problem at late development stages can add significant cost and delays to initial schedules, eventually leading to company's bankruptcy. Sound testing methods are thus needed to reduce the uncertainties, increase confidence in results, assist and guide the concept and subcomponents design, and thus largely assist in the decision-making progress. **The new hybrid testing platform with open access** for models, testbeds and improved data management are all necessary to lower the cost on future technologies.

If you like to find out more about the VALID project, please visit **https://www.validhtp.eu/**

Privacy Policy:
By completing and submitting this form, you agree that the data you provide can be used by the VALID Project. The data is only used for the purpose and duration of the VALID project.

The data you provide will be used in compliance with the GDPR, data protection principles in Regulation (EC) 2016/679 (more information can be found on the official website: https://gdpr.eu/)

If you have any questions regarding the Privacy Policy, do not hesitate to contact us via email to fabiola.roccatagliata@rina.org

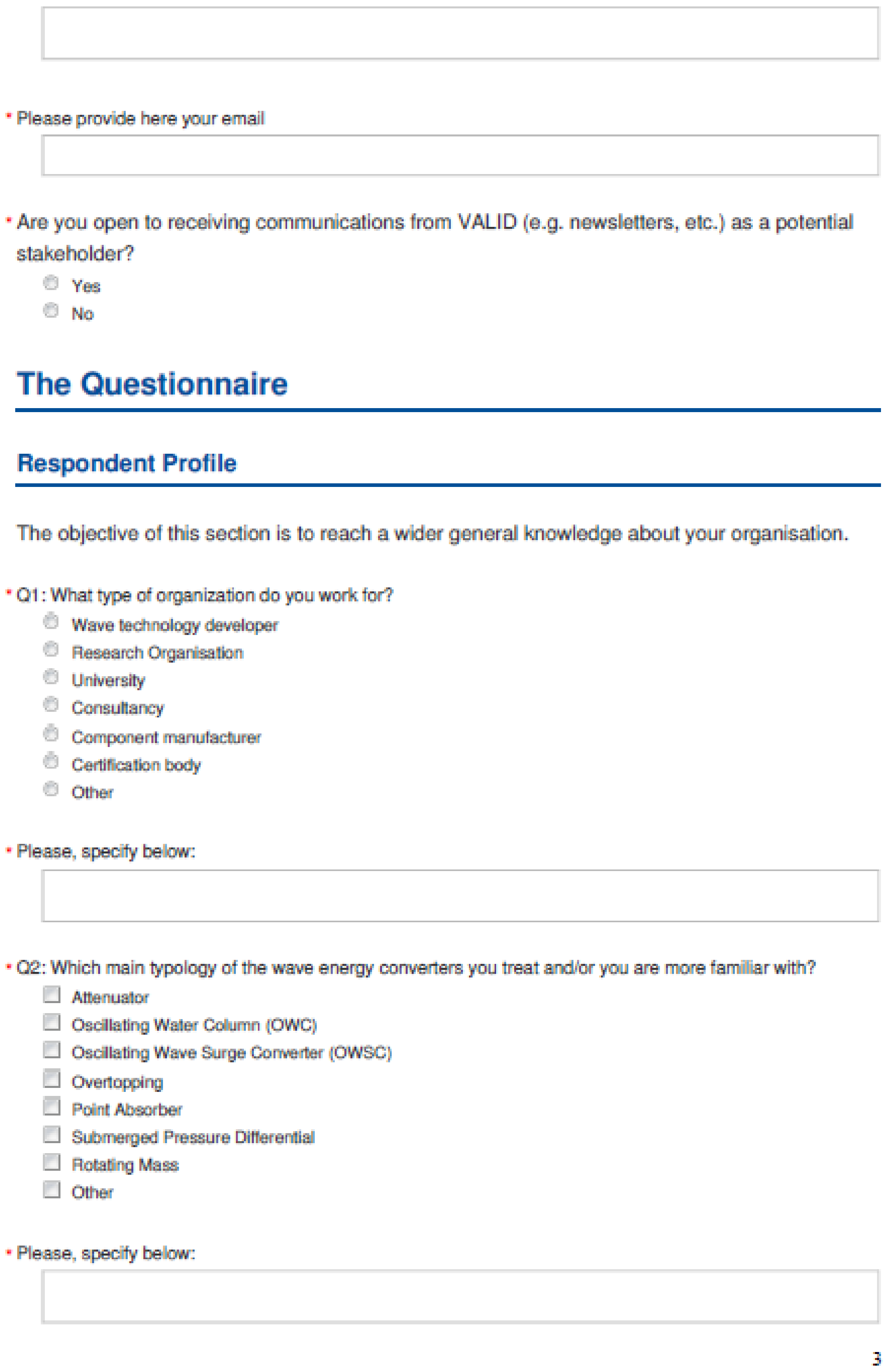
The privacy policy for the survey is available here:
VALID_T1.1_survey_privacy_policy.pdf

* I have read and agree to the VALID Survey Privacy Policy
○ Yes
○ No

* Last Name

* First Name

2



* Please provide here your email

* Are you open to receiving communications from VALID (e.g. newsletters, etc.) as a potential stakeholder?
- ○ Yes
- ○ No

The Questionnaire

Respondent Profile

The objective of this section is to reach a wider general knowledge about your organisation.

* Q1: What type of organization do you work for?
- ○ Wave technology developer
- ○ Research Organisation
- ○ University
- ○ Consultancy
- ○ Component manufacturer
- ○ Certification body
- ○ Other

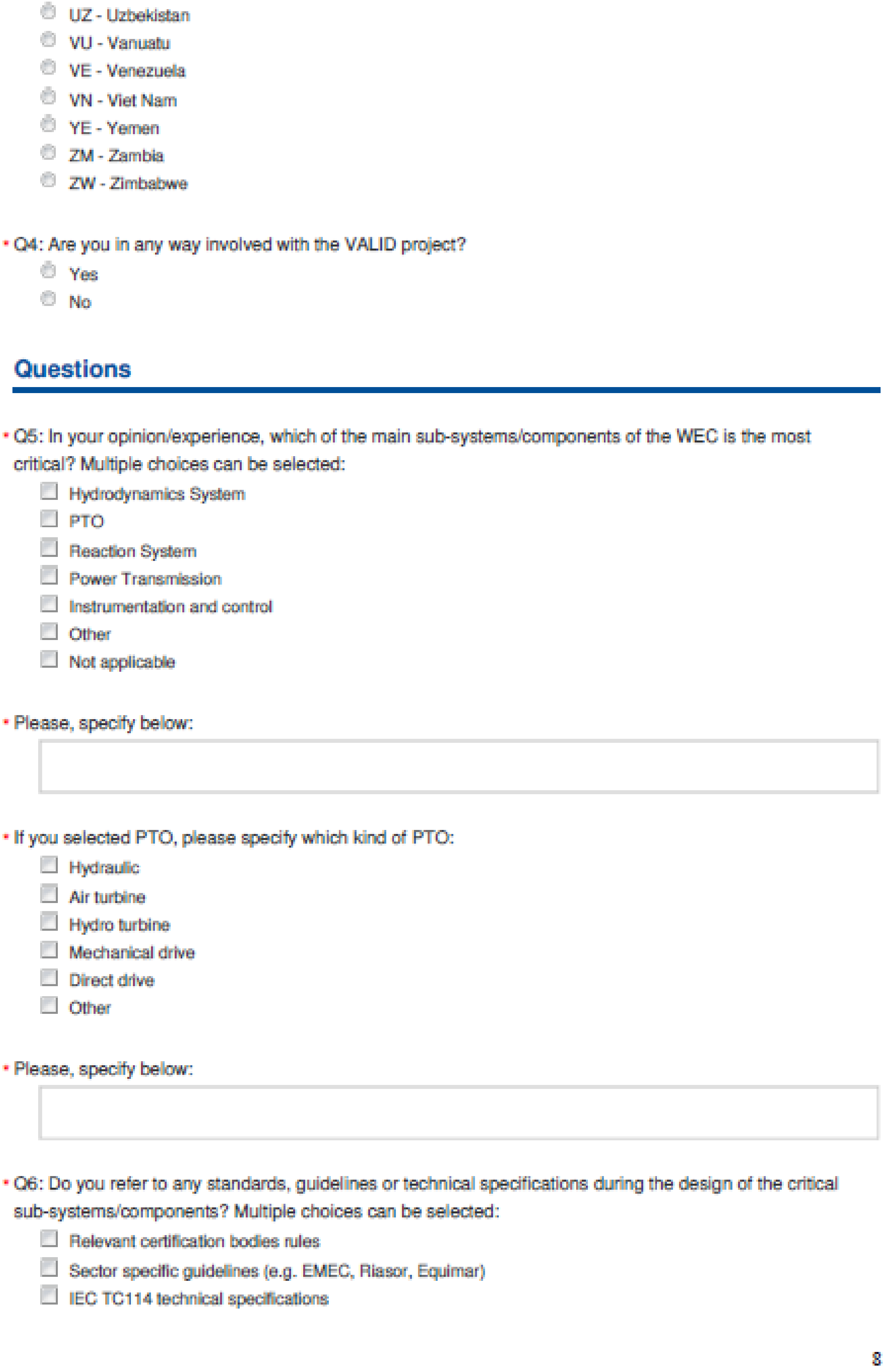
* Please, specify below:

* Q2: Which main typology of the wave energy converters you treat and/or you are more familiar with?
- ☐ Attenuator
- ☐ Oscillating Water Column (OWC)
- ☐ Oscillating Wave Surge Converter (OWSC)
- ☐ Overtopping
- ☐ Point Absorber
- ☐ Submerged Pressure Differential
- ☐ Rotating Mass
- ☐ Other

* Please, specify below:

3

* Q3: Which Country are you from?
- ○ AF - Afghanistan
- ○ AL - Albania
- ○ DZ - Algeria
- ○ AD - Andorra
- ○ AO - Angola
- ○ AG - Antigua and Barbuda
- ○ AR - Argentina
- ○ AM - Armenia
- ○ AU - Australia
- ○ AT - Austria
- ○ AZ - Azerbaijan
- ○ BS - Bahamas
- ○ BH - Bahrain
- ○ BD - Bangladesh
- ○ BB - Barbados
- ○ BY - Belarus
- ○ BE - Belgium
- ○ BZ - Belize
- ○ BJ - Benin
- ○ BT - Bhutan
- ○ BO - Bolivia
- ○ BA - Bosnia and Herzegovina
- ○ BW - Botswana
- ○ BR - Brazil
- ○ BN - Brunei Darussalam
- ○ BG - Bulgaria
- ○ BF - Burkina Faso
- ○ BI - Burundi
- ○ CV - Cabo Verde
- ○ KH - Cambodia
- ○ CM - Cameroon
- ○ CA - Canada
- ○ CF - Central African Republic
- ○ TD - Chad
- ○ CL - Chile
- ○ CN - China
- ○ CO - Colombia
- ○ KM - Comoros
- ○ CG - Congo
- ○ CR - Costa Rica
- ○ CI - Côte D'Ivoire
- ○ HR - Croatia
- ○ CU - Cuba
- ○ CY - Cyprus
- ○ CZ - Czechia
- ○ CD - Democratic Republic of the Congo
- ○ DK - Denmark
- ○ DJ - Djibouti
- ○ DM - Dominica
- ○ DO - Dominican Republic
- ○ EC - Ecuador
- ○ EG - Egypt
- ○ SV - El Salvador
- ○ GQ - Equatorial Guinea
- ○ ER - Eritrea
- ○ EE - Estonia
- ○ SZ - Eswatini
- ○ ET - Ethiopia
- ○ FJ - Fiji
- ○ FI - Finland
- ○ FR - France
- ○ GA - Gabon
- ○ GM - Gambia
- ○ GE - Georgia
- ○ DE - Germany
- ○ GH - Ghana
- ○ GR - Greece
- ○ GD - Grenada
- ○ GT - Guatemala
- ○ GN - Guinea
- ○ GW - Guinea Bissau
- ○ GY - Guyana
- ○ HT - Haiti
- ○ HN - Honduras
- ○ HU - Hungary
- ○ IS - Iceland
- ○ IN - India
- ○ ID - Indonesia
- ○ IR - Iran
- ○ IQ - Iraq
- ○ IE - Ireland
- ○ IL - Israel
- ○ IT - Italy
- ○ JM - Jamaica
- ○ JP - Japan
- ○ JO - Jordan
- ○ KZ - Kazakhstan
- ○ KE - Kenya
- ○ KI - Kiribati
- ○ KW - Kuwait
- ○ KG - Kyrgyzstan
- ○ LA - Laos
- ○ LV - Latvia
- ○ LB - Lebanon
- ○ LS - Lesotho
- ○ LR - Liberia
- ○ LY - Libya
- ○ LI - Liechtenstein
- ○ LT - Lithuania
- ○ LU - Luxembourg
- ○ MG - Madagascar
- ○ MW - Malawi
- ○ MY - Malaysia
- ○ MV - Maldives
- ○ ML - Mali
- ○ MT - Malta
- ○ MH - Marshall Island:
- ○ MR - Mauritania
- ○ MU - Mauritius
- ○ MX - Mexico
- ○ FM - Micronesia
- ○ MC - Monaco
- ○ MN - Mongolia
- ○ ME - Montenegro
- ○ MA - Morocco
- ○ MZ - Mozambique
- ○ MM - Myanmar
- ○ NA - Namibia
- ○ NR - Nauru
- ○ NP - Nepal
- ○ NL - Netherlands
- ○ NZ - New Zealand
- ○ NI - Nicaragua
- ○ NE - Niger
- ○ NG - Nigeria
- ○ KP - North Korea
- ○ MK - North Macedoni
- ○ NO - Norway
- ○ OM - Oman
- ○ PK - Pakistan
- ○ PW - Palau
- ○ PA - Panama
- ○ PG - Papua New Gui
- ○ PY - Paraguay
- ○ PE - Peru
- ○ PH - Philippines
- ○ PL - Poland
- ○ PT - Portugal
- ○ QA - Qatar
- ○ MD - Republic of Moldova
- ○ RO - Romania
- ○ RU - Russian Federation
- ○ RW - Rwanda
- ○ KN - Saint Kitts and Nevis
- ○ LC - Saint Lucia
- ○ VC - Saint Vincent and the Grenadines
- ○ WS - Samoa
- ○ SM - San Marino
- ○ ST - Sao Tome and Principe
- ○ SA - Saudi Arabia
- ○ SN - Senegal
- ○ RS - Serbia
- ○ SC - Seychelles
- ○ SL - Sierra Leone
- ○ SG - Singapore
- ○ SK - Slovakia
- ○ SI - Slovenia
- ○ SB - Solomon Islands
- ○ SO - Somalia
- ○ ZA - South Africa
- ○ KR - South Korea
- ○ SS - South Sudan
- ○ ES - Spain
- ○ LK - Sri Lanka
- ○ SD - Sudan
- ○ SR - Suriname
- ○ SE - Sweden
- ○ CH - Switzerland
- ○ SY - Syrian Arab Republic
- ○ TJ - Tajikistan
- ○ TZ - Tanzania
- ○ TH - Thailand
- ○ TL - Timor-Leste
- ○ TG - Togo
- ○ TO - Tonga
- ○ TT - Trinidad and Tobago
- ○ TN - Tunisia
- ○ TR - Turkey
- ○ TM - Turkmenistan
- ○ TV - Tuvalu
- ○ UG - Uganda
- ○ UA - Ukraine
- ○ AE - United Arab Emirates
- ○ GB - United Kingdom
- ○ US - United States of America
- ○ UY - Uruguay



○ UZ - Uzbekistan
○ VU - Vanuatu
○ VE - Venezuela
○ VN - Viet Nam
○ YE - Yemen
○ ZM - Zambia
○ ZW - Zimbabwe

* Q4: Are you in any way involved with the VALID project?

○ Yes
○ No

Questions

* Q5: In your opinion/experience, which of the main sub-systems/components of the WEC is the most critical? Multiple choices can be selected:

☐ Hydrodynamics System
☐ PTO
☐ Reaction System
☐ Power Transmission
☐ Instrumentation and control
☐ Other
☐ Not applicable

* Please, specify below:

* If you selected PTO, please specify which kind of PTO:

☐ Hydraulic
☐ Air turbine
☐ Hydro turbine
☐ Mechanical drive
☐ Direct drive
☐ Other

* Please, specify below:

* Q6: Do you refer to any standards, guidelines or technical specifications during the design of the critical sub-systems/components? Multiple choices can be selected:

☐ Relevant certification bodies rules
☐ Sector specific guidelines (e.g. EMEC, Riasor, Equimar)
☐ IEC TC114 technical specifications

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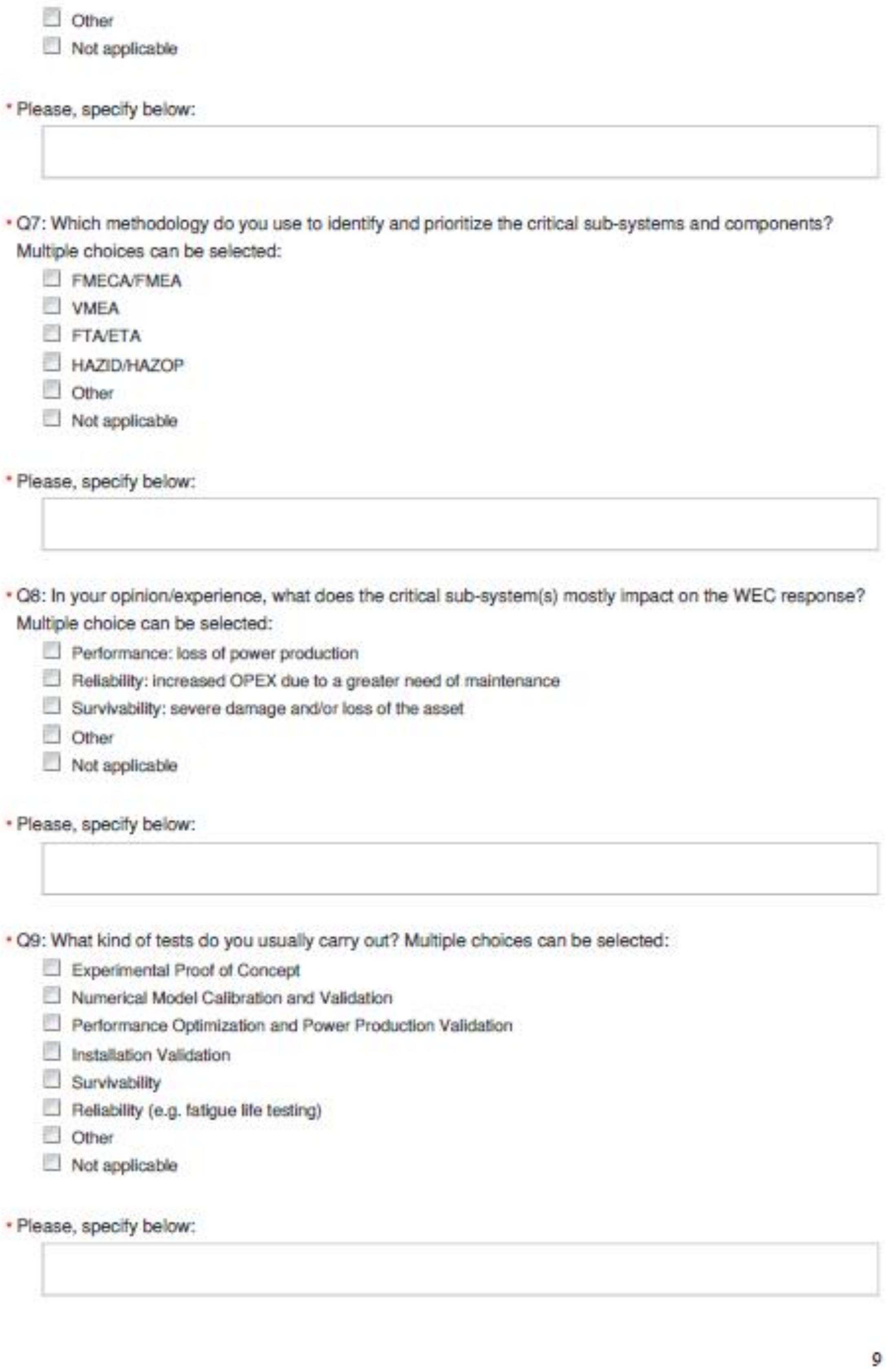


☐ Other
☐ Not applicable

* Please, specify below:

* Q7: Which methodology do you use to identify and prioritize the critical sub-systems and components? Multiple choices can be selected:

☐ FMECA/FMEA
☐ VMEA
☐ FTA/ETA
☐ HAZID/HAZOP
☐ Other
☐ Not applicable

* Please, specify below:

* Q8: In your opinion/experience, what does the critical sub-system(s) mostly impact on the WEC response? Multiple choice can be selected:

☐ Performance: loss of power production
☐ Reliability: increased OPEX due to a greater need of maintenance
☐ Survivability: severe damage and/or loss of the asset
☐ Other
☐ Not applicable

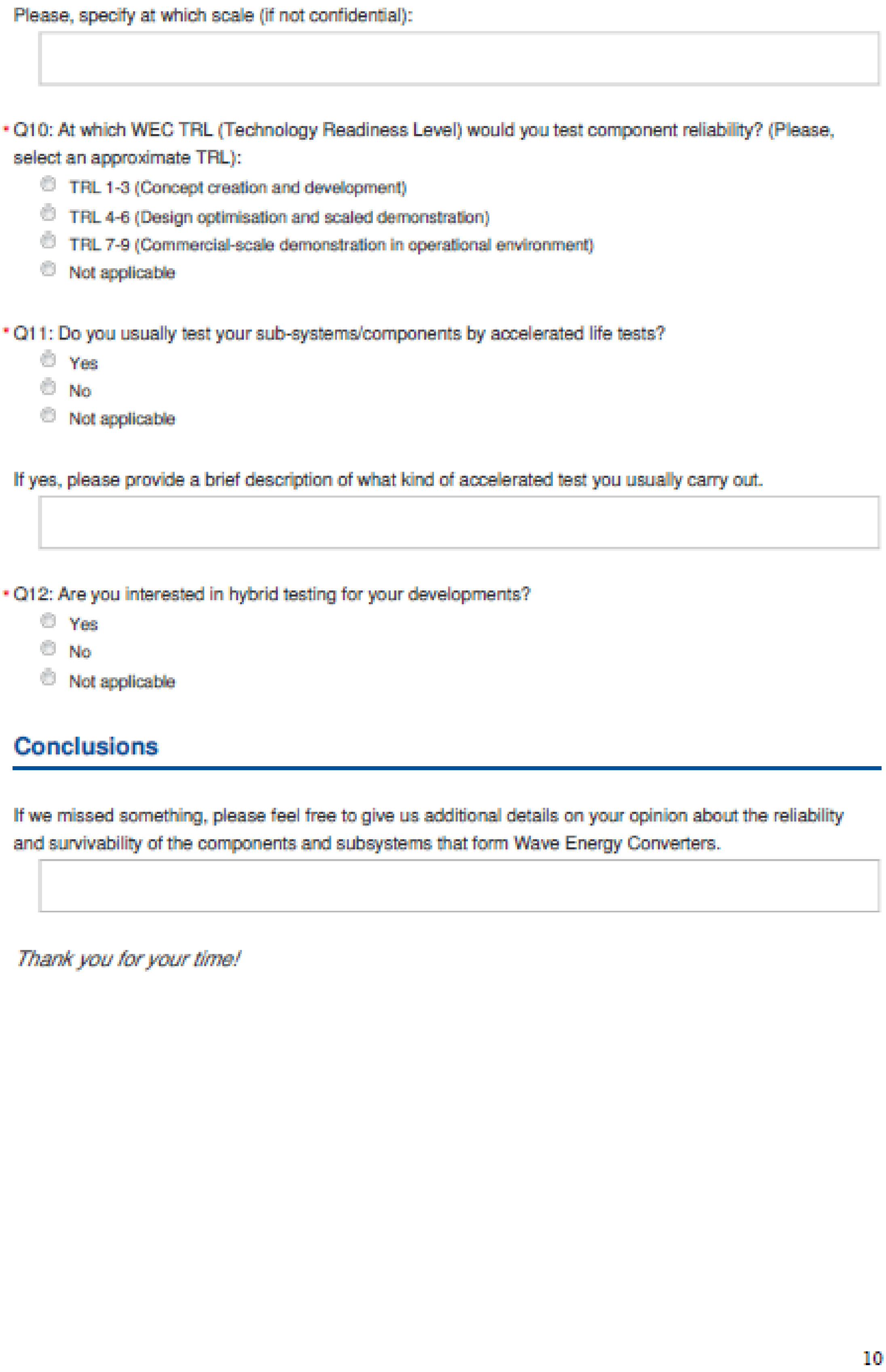
* Please, specify below:

* Q9: What kind of tests do you usually carry out? Multiple choices can be selected:

☐ Experimental Proof of Concept
☐ Numerical Model Calibration and Validation
☐ Performance Optimization and Power Production Validation
☐ Installation Validation
☐ Survivability
☐ Reliability (e.g. fatigue life testing)
☐ Other
☐ Not applicable

* Please, specify below:

9



Please, specify at which scale (if not confidential):

* Q10: At which WEC TRL (Technology Readiness Level) would you test component reliability? (Please, select an approximate TRL):

○ TRL 1-3 (Concept creation and development)
○ TRL 4-6 (Design optimisation and scaled demonstration)
○ TRL 7-9 (Commercial-scale demonstration in operational environment)
○ Not applicable

* Q11: Do you usually test your sub-systems/components by accelerated life tests?

○ Yes
○ No
○ Not applicable

If yes, please provide a brief description of what kind of accelerated test you usually carry out.

* Q12: Are you interested in hybrid testing for your developments?

○ Yes
○ No
○ Not applicable

Conclusions

If we missed something, please feel free to give us additional details on your opinion about the reliability and survivability of the components and subsystems that form Wave Energy Converters.

Thank you for your time!

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Annex B: DLC table (adapted from [16])

Design situation	**DLC**	**Wave conditions**	**PTO conditions**	**Other conditions**	**Type of analysis**	**Partial safety factors**
1. Power Production	1.1	*NSS*	*Power Production*	NCM	F U	* N
	1.2	*RNSS*	*Power Production*	NCM MCD	U	N
	1.3	*RNSS*	*Power Production*	Range of spectral shapes, including bimodal seas	U	N
	1.4	*FWG*	*Power Production*		U	E
	1.5	*FWG*	*Power Production*	Grid Loss	F U	* E
	1.6	*RNSS*	*Power Production*	Marine growth or freeboard ice accumulation	U	N
2. Power production plus occurrence of fault	2.1	*RW* *FWG*	*Power Production*	Fault in control system(s)	U	N
	2.2	*RW* *FWG*	*Power Production*	Fault in safety system or preceding internal electrical fault	U	E
	2.3	*RW* *FWG*	*Power Production*	Fault in the control or safety system(s)	F	*
3. Start-up	3.1	*RNSS*	*Start-up Procedure*		F U	* N
4. Normal shut-down	4.1	*FWG*	*Normal Shutdown Procedure*	Vary shut-down time to different points during the wave group	F	*
	4.2	H_{s1}	*Normal Shutdown Procedure*		F U	* N
5. Emergency shut-down	5.1	*FWG*	*Power Production*		U	N
6. Parked (standstill or idling)	6.1	*ESS* - H_{s1}	*Parked*	NCM	U	N
	6.2	*ESS* - H_{s50}	*Parked*	Tide height/current due to storm surge	U	E
	6.3	*ESS* - H_{s50}	*Parked*	Grid loss	U	E
	6.4	*NSS*	*Parked*		F	*
7. Parked plus fault conditions	7.1	*ESS* - H_{s1}	*Parked*	Fault condition	U	N
	7.2	*ESS* - H_{s50}	*Parked*		U	E
	7.3	*NSS*	*Parked*		F	*

Design situation	**DLC**	**Wave conditions**	**PTO conditions**	**Other conditions**	**Type of analysis**	**Partial safety factors**
8. Transport, installation, maintenance and repair	8.1	*NSS* - H_{s_T}	*Transportation configuration*	To be specified by manufacturer (transport / tow)	U	T
	8.2	*RNSS*	*Installation configuration*	To be specified by manufacturer (installation / removal)	U	T
	8.3	*RNSS*	*Maintenance configuration*	To be specified by manufacturer (including tidal currents where applicable)	U	T
	8.4	*RNSS*	*Maintenance configuration*	Absence of grid for long period	F U	* T
	8.5	*NSS* - H_{s_T}	*Maintenance configuration*	Collision with transport or installation vessels	U	T
	8.6	*ESS* - H_{s1}	*Locked in maintenance configuration*		U	T
9. Accidental / Abnormal Events	9.1	*RW*	*Power Production*	Ship impact Instantaneous load applied to each of the largest bodies in the system	U	A
	9.2	*RW*	*Power Production*	Ice impact Instantaneous load applied to each of the largest bodies in the system	F U	* A
	9.3	*Tsunami due to earthquake/cyclone*	*Controller in survival mode (if this can be done remotely)* *Otherwise: Power Production*	None	U	A
	9.4	*NSS*	*Power Production*	Varying ground conditions	F U	* A

Design situation	**DLC**	**Wave conditions**	**PTO conditions**	**Other conditions**	**Type of analysis**	**Partial safety factors**
10. Damaged stability	10.1	*NSS*	*Power Production*	Transient condition between intact and redundancy check condition	U	A
	10.2	*NSS*	*Power Production*	Single mooring line failure, redundancy check.	U	A
	10.3	*NSS*	*Power Production*	Leakage (damaged stability)	U	A
	10.4	*ESS - H_{s50}*	*Parked*	Transient condition between intact and redundancy check condition	U	A
	10.5	*ESS - H_{s50}*	*Parked*	Single mooring line break, redundancy check	U	A
	10.6	*ESS - H_{s50}*	*Parked*	Leakage (damage stability)	U	A