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Verification through Accelerated testing Leading to Improved wave energy Designs

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VALID Standardization
and Regulatory inventory
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Executive Summary

The present report constitutes Deliverable 6.1 “VALID standardization and Regulatory Inventory”, developed within WP6 of VALID.

Standardisation is an often-neglected route for exploiting of research results. The VALID project will produce significant results informing about the current standardisation activities.

The main aim of D6.1 is to provide an overview of available standards and regulations relevant to Wave Energy Converters. In particular, the documents identified in D1.1 have been used as a starting point for the state of art of regulations presented this report. Regulations directly produced for WEC technologies together with standards and guidelines related to other offshore marine application that can be applied to WECs have been presented and described.

Moreover, an accurate description on the IEC TC 114 62600 series, that is conducting the standardization at an international level, has been presented. Also, a gap analysis assessing possible areas of shortcomings in the current standards and regulations is included, together with an evaluation of potential improvement and evolutions.

Project partner names

- RISE Research Institutes of Sweden AB
- Fundacion Tecnalia Research and Innovation
- Corpower Ocean AB
- RINA Consulting S.p.A.
- Biscay Marine Energy Platform SA
- IDOM Consulting, Engineering, Architecture, S.A.U.
- Aalborg University
- AVL List GMBH
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1 Introduction

This report - Deliverable 6.1 "VALID Standardization and Regulatory inventory" - is a public document produced in the framework of the VALID project. It relates to work conducted under WP6 "Overall Assessment and Standardisation", and more specifically under Task 6.1 "Overall Assessment and Standardisation". In this section, the aim of this deliverable is introduced.

1.1 Aim

This document aims to assess existing standards and regulations relevant to Wave Energy Converters (WECs) and to identify the potential areas of improvement in the technical specifications, to liaise with IEC technical committees. In this task, in addition to what was already introduced and briefly described in D1.1 of the VALID project "*Accelerated Testing Requirements*", the analysis is mainly focused on the **IEC 62600 series**, "*Marine Energy - Wave, Tidal and Other Water Current Converters*" [1], that is a set of standards relevant to the marine energy sector and is being developed by the International Electrotechnical Commission (IEC) technical committee TC114. At present, there are no standards and regulations specifically relevant to WECs, thus the IEC 62600 series could be an important landmark for all the marine energy technologies.

A specific set of standards and regulations will also facilitate the standardization process, with the expected long-term consequence of improving and optimizing WECs technology in terms of simplicity of design, reliability, cost reduction, improvement of performances and efficiency.

1.2 Methodology

Wave energy converters (WECs) are designed to convert hydrodynamic forces into usable energy, and they can present similarities as well as fundamental differences from other marine systems. In the last years, the marine energy converter industry has been committed to the process of creating new standards and guidance that could be applied to this emerging sector, in order to increase the associated level of Technology Readiness Level (TRL) and consequently, promote and facilitate its development. These technologies cover a wide spectrum of disciplines and for this reason some of these documents have been produced adapting existing standards and guidance from other marine sectors, i.e., Oil & Gas and offshore wind.

Existing standards and regulations cover some of the aspects of the design of WEC systems, however, due to the relatively novelty of these technologies and the high number of different concepts and operating principles, there are still several areas of standards and guidelines that need to be implemented or improved.

2 Inputs from D1.1

The main scope of D1.1 of VALID project "*Accelerated Testing Requirements*" is to analyse the WEC-system breakdown, the critical sub-systems and components, their related parameters, and the associated design requirements for representative ocean energy converters. Moreover, the report is focused on high-level definition of accelerated testing requirements and a first desktop study to identify best practices and standards related to WEC technologies has been already performed in D1.1. The aim of this section is to recall these documents, listed below, while a more detailed description of their contents is given in the next section.

- DNV "Guidelines on Design and Operation of Wave Energy Converters", May 2005, The Carbon Trust [2];
- DNV-OSS-312 "Certification of Tidal and Wave Energy Converters", October 2008 [3];
- EMEC "Guidelines for Design Basis of Marine Energy Conversion Systems", 2009 [4];
- IEA-OES "An International Evaluation and Guidance Framework For Ocean Energy Technology", 2021 [5].

The design process of WEC systems can be integrated and supported by standards and guidelines used in similar offshore applications, such as maritime, oil & gas and offshore wind. Relevant standards identified in D1.1 are presented below and a general overview, focusing on useful aspects applicable to WECs is given in the next section:

- GL Rules and Guidelines IV-6-4 (2007) Rules for Classification and Construction IV Industrial Services [6];
- GL Rules and Guidelines IV-2-5 (2012) Guideline for the Certification of Offshore Wind Turbines - Strength Analyses [7];
- DNVGL-ST-0119 (2018) Floating Wind Turbine Structures [8].

3 Assessment of existing standards, guidelines and regulations

This section presents an assessment of the existing regulations, standards and guidelines that can be applied to WECs.

In general, standards are drawn up by governmental or professional companies and include definitions, technical specifications and guidelines ensuring safety of operations, quality of materials, final product and processes. Utilization of standards in not mandatory, but generally recommended in order to facilitate the harmonization process of the relevant technology.

Regulations, on the contrary, are mandatory legal requirements. They are issued by government and relevant authorities.

3.1 DNV "Guidelines on Design and Operation of Wave Energy Converters", May 2005, The Carbon Trust [2]

The main objective of this guideline is to collect existing codes and standards from the offshore industries and to provide interpretation and guidance in the application of these documents to wave energy converters. It mainly covers the aspects of concept development, design, construction, and life cycle process.

The document initially focuses on the qualification process of an unproven technology. It is underlined its fundamental role in the development of new technologies, how it contributes to reduce the level of uncertainty, supports the definition of the service life performances and costs of these devices. More in particular, the authors adapt the qualification process presented in DNV RP-A203 [9] to marine renewable technologies. Then, failure mode identification and risk ranking are discussed, giving a short list on the common technique used to carry out this analysis, focusing on the SWIFT method and providing a semi-qualitative method to determine the risk level. After that, referring to BS EN 12973:2000, a general overview on the value management tool and the life cycle analysis is given. The following Section covers the aspects of reliability and costs, treating the aspect of system design optimization in order to obtain the lowest production costs per produced kWh. Furthermore, reliability issues, Life Cycle Cost (LCC), Fault Tree Analysis (FTA) and failure mode and effects analysis (FMECA) are presented, and several standards related to these topics are listed. Then, the guideline moves to the risk involved in the life cycle of these devices, giving a list of the category of events included in a typical offshore risk assessment, making considerations on the relative consequences of failure. The general aspects and stakeholders that should be considered to derive a safety philosophy are presented, and safety classes are defined. Referring to RP-A201, a list of elements that should be included in the documentation provided by designer and developer are provided. Successively, material selection is discussed, highlighting the main properties of steel, concrete and composite materials; corrosion protection is addressed. At this point, the document covers more technical design aspects such as: structural design criteria, foundation design, mooring system analysis, stability and watertight integrity etc. Considerations on the manufacturing process are made, focusing on manufacturing surveys, steel structures and minimum structural requirements. The last sections cover the typical aspects for WEC systems of installation and temporary phase, commissioning, in-service phases such as operations and maintenance, and decommissioning. Finally, the statutory regulations and requirements that the device must satisfy are discussed.

3.2 DNV-OSS-312 Certification of Tidal and Wave Energy Converters, October 2008 [3]

This specification presents principles and procedures applicable to wave energy devices. These relatively new technologies are characterized by high risks and uncertainties related to the lack of operational experience in the offshore renewable industry. In this document DNV has taken advantage of its experience in the oil and gas industry and adapt it, where possible, to the relevant safety level necessary for renewable energy devices, considering that wave energy devices installed offshore would be facing many of the same environmental challenges as Oil & Gas installations. The aim of this specification is to define a robust process that can be followed to provide evidence to stakeholders that the marine energy system under examination will comply to relevant standards and satisfy acceptable levels of safety, availability, reliability, asset integrity and environmental impact. The document is divided into three main sections:

- Section 1 which provides a general introduction to the DNV document hierarchy, describing the three types of categories for DNV offshore publications: offshore service specifications, offshore standards and recommended practices. A short explanation on verbal forms and definitions is given, together with a list of relevant DNV documents for tidal and wave energy converters. Then, considerations on safety philosophy are made, separating structures from equipment and systems. Finally, in this section certification documents and processes are described.
- Section 2, which covers principles of certification, qualification of new technologies, procedures for assignment of certification and verification of procured items.
- Section 3 that presents the typical documentation to be submitted related to a tidal or wave energy converter. The topics covered are structural design, position keeping, machinery and marine systems, electrical systems, instrumentation and control systems, fire protection and safety systems.

3.3 EMEC "Guidelines for Design Basis of Marine Energy Conversion Systems", 2009 [4]

This document has been written in consultation with the European Marine Energy Centre Ltd (EMEC) together with other interested parties of the UK marine energy community and it is part of the Marine Renewable Energy Guides series, which is composed by twelve documents.

The scope of these guidelines is to provide general principles and guidance in the design of wave and tidal stream energy converters. The document covers all the aspects of the design process, focusing on parameters and factors that can influence the design of this type of devices and presenting the design procedures that can be followed. The concept design is not considered in these guidelines, as it is expected that the designer has already defined the general layout, the operational function, and have performed numerical and modelling tests.

Moreover, it aims to provide a basis document that the designer could follow in order to develop and optimize the device for manufacturing. It provides a step-by-step guidance to achieve a conforming design that would also comply with the Certification Scheme. The topics and design aspects covered in this document are:

- The management of the design process in terms of quality assurance, identification of the associated risks, health and safety, environmental impact, consultations, permissions and standards hierarchy;
- Elements that should be outlined in the description of the device and design life basic principles;

- Guidance on the various environmental phenomena that the system will be facing, highlighting key process or data that need to be considered in the design process;
- A loading guidance with the description of the types of loads that the design basis should take into account and design concepts that can be used to determine the suitability of the design of the device;
- A fatigue design guidance that treats fatigue loading and analysis methods;
- A description of the harmonic response of the system, particularly important in this field considering that many WEC's concepts work close to resonant frequencies in order to maximize the power captured;
- A list of standards for materials in order to achieve consistency and uniformity;
- Corrosion and how to protect the device from the highly corrosive marine environment;
- Aspects that should be considered in the design of a floating structure and relative stability;
- Design of foundation and support structures;
- Design of mooring systems;
- Considerations on mechanical and electrical components of marine renewable energy converters and international standards that they should comply with;
- A general guidance on the requirements for instrumentation and control systems;
- Cable connection to shore;
- Fabrication, manufacture and commissioning;
- Deployment, retrieval, operational and decommissioning phases that should be carefully considered in order to minimize life cycle costs;

3.4 IEA-OES "An International Evaluation and Guidance Framework For Ocean Energy Technology", 2021 [5]

This document is prepared by the members of the International Energy Agency (IEA) Ocean Energy Systems (OES) Technology Collaboration Programme (TCP) and it is developed within the activity of IEA-OES Task 12.

The scope is to provide a framework for technology evaluation and guidance in order to support international efforts and providing consistent information to decision-makers of the ocean energy sector. More in particular, it includes technology associated with utility-scale electricity generation from ocean waves and tidal streams and it covers the full technology development from concept creation to commercial readiness. Future Task 12 activity will expand to incorporate other forms of ocean energy. Most of the guidance presented in this document is 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.

As stated in [5] *"The goal of this document is to create a solid foundation for the unambiguous development and evaluation process, accommodating formal standards and guidelines, where they already exist, and providing cues for the future production of other supporting standards and guidelines where required. The goal is not to replace existing technical specifications, standards and guidance, but to unite them with a common purpose".*

The final goal of the wider activity is to create a complete and unambiguous process for the development and evaluation of ocean energy technologies throughout all stages of development.

This document is divided into three main sections:

- Section 1 that introduces the concept and content of the Evaluation and Guidance framework. A high-level discussion of the importance of technology evaluation and guidance in the ocean energy sector is carried out.
- Section 2 that presents the detail of the stages and topics included in the framework and a discussion of the integration of topics into a holistic evaluation process.
- Section 3 that explains the criteria used to evaluate technologies and recommended engineering activities that should be carried out at each stage of the technology development process.

3.5 IEC 62600 Series

The International Electrotechnical Commission (IEC) is developing a set of standards for the Marine Energy sector, the IEC 62600 series, "Marine Energy - Wave, Tidal and Other Water Current Converters"[1], which cover different aspects and various type of marine energy devices. Some of these documents are published as Technical Specifications with a maintenance team assigned, and others are under development by project teams. The IEC technical committees have as main task the development and publication of international standards, however there are circumstances in which the technical committees can decide to propose technical specifications. More in particular, this decision can be taken when:

- The required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

These technical specifications are reviewed within three years from the date of publication to decide if they can be transformed into International Standards. The scope of this standardization process is to accelerate innovation, facilitate industrialization, reduce uncertainties and increase acceptance of these technologies and devices.

These technical specifications cover different aspects and areas of the various Marine Energy Converters (MEC), from a first group of generic documents that gathers general information on these technologies, to Technical Specifications that treat more specific topics. More in detail, Figure 1 gives a general overview of this series of standards and the main aspects covered.

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 1: Overview of IEC TC 114 62600 series of standards for marine and water current energy converters.

The technical specifications most relevant to the scope of the VALID project have been identified and presented below. A brief description is given, highlighting the main topics and areas covered, in order to understand the state of art and create a starting point for the gap analysis carried out in Section 4.

3.5.1 TS2: Design requirements for marine energy systems (proposed stability date 2021) [10]

This technical specification is applicable to wave, ocean tidal and current energy converters, which are collectively indicated as marine energy converters (MEC). The purpose of this document is to provide design requirements to ensure the engineering integrity and an appropriate level of protection in order to prevent possible damages and consequent failure of the MEC systems. It mainly covers the aspects of structural, mechanical, electrical and control systems design, taking into consideration their interaction and interfaces with other elements of the marine energy converter installation, as illustrated in Figure 2.

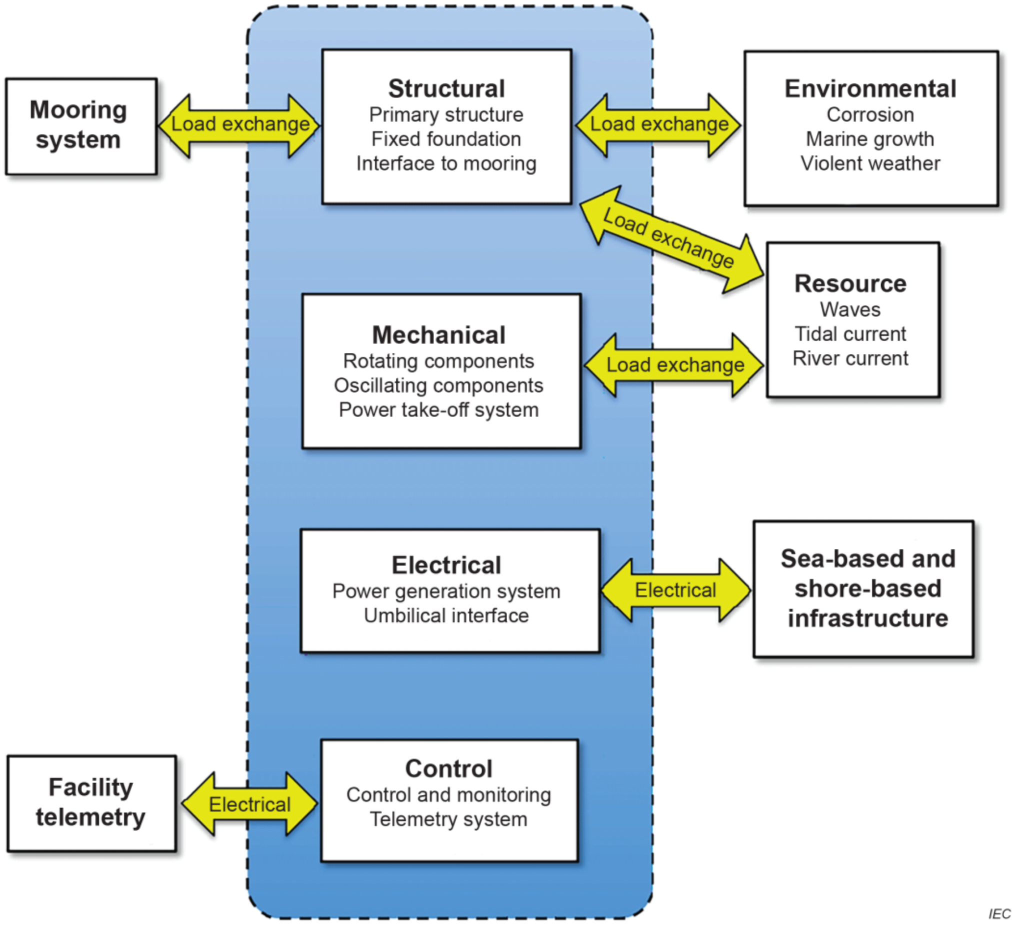

Figure 2: Marine energy converter system boundary for IEC TS 62600-2 and interfaces [10]

This document does not cover all the aspects of the engineering process typically considered during the entire system's design. More in particular, it does not address energy production, performance efficiency, environmental impacts, electric generation and transmission, ergonomics, or power quality. However, since the overall objective of the IEC 62600 series is to cover the full design process of MEC systems, it is highlighted that all the topics mentioned above are treated and discussed in other documents of this series. This technical specification ensures MEC reliability utilizing partial safety factors for loads and materials in accordance with ISO 2394 and it can be applied to MECs from the preliminary design stage to advanced prototypes, as well as to those that have reached commercial deployment.

A general overview on the principal elements that should be considered in WECs design is given. The topics discussed are: design objectives, risk assessment, safety levels, basis of design, load definition, limit state design, structural modelling and analysis. These topics are common to all marine energy devices, however for some of them, considerations and calibrations to the WEC industry are needed and presented in this document. Moreover, the process to carry out a technology assessment is described, explaining how to define the relative degrees of novelty and application area, which is a fundamental step in the development of new technologies.

The typical environmental conditions faced by a MEC are described together with relative formulations to estimate extreme events, which is a well-known section common in the design guidelines of all marine devices. The combination of environmental conditions, design categories and design conditions used to compose the design cases and determine the design loads are explained and discussed. Limit states, such as ultimate, fatigue, serviceability, accidental limit states, beyond which the MEC no longer satisfies the design requirements, and load case modelling and simulation are described. Partial safety factors are discussed, underlining that, due to the fact that many of these technologies are new and unverified, these factors need to be calibrated for MECs and may need to be modified. One section is dedicated to providing general principles, engineering guidance and requirements for material selection for all parts of MEC installations. Procedures to ensure structural integrity of steel, concrete and composite structures are presented, with particular attention to the relative partial safety factor.

Another section is focused on describing electrical, mechanical, instrumentation and control systems that can have critical impact on the operability and integrity of the MEC.

Additional requirements for the consideration of MEC mooring systems, station keeping, including the design of geotechnical interface, are presented. The last section contains considerations about the life cycle of MECs, covering extraordinary design conditions that may be experienced over the operating life of the device.

3.5.2 TS3: Measurement of mechanical loads (proposed stability date 2023) [11]

The structural design process is a fundamental step in the design of a MEC, and an accurate quantification of the loads acting on the system is consequently of crucial importance. In the preliminary stages of the design, loads are estimated through simulations and mathematical models, which present their restrictions, approximations and relative uncertainties. It is underlined that for this reason, these models should be validated by load measurements.

This document describes the specifications for the full-scale mechanic loads measurement on hydrodynamic MECs. It is applicable from the last prototype stage to the first production device, which correspond to a TRL that ranges from 7 to 9. Moreover, it presents requirements to carry out mechanical load tests in such a way that they would produce consistent and reproducible results. These measurements can be used both as basis for the design and as basis for certification. This topic has been already well treated in the wind turbines sector and this document can be compared to the international wind standards IEC 61400-13. Where possible, the same testing methods, already developed for the wind sector, are applied.

Testing methods are described and informative annexes to support their understanding are provided. Tests requirements and recommendations presented in this document can be applied to a specific MEC technology through a technology qualification process. Moreover, the tests outlined in this technical specification are aligned with the design load cases presented in IEC TS 62600-2.

The topic of blades and relative connection to a rotor shaft is treated in detail due to the common presence in MECs systems and the high knowledge about these sub-components.

Test site requirements, such as bathymetry and metocean conditions, and circumstances in which a subsystem or structural components need to be separated from full-scale testing and tested in laboratory, are presented. Particular attention is given to the measured load cases (MCLs) necessary to perform a proper model validation, which are defined according to the design load cases (DLCs) described in IEC TS 62600-2. In this section it is recommended to record a minimum number of load cases, which could depend on the MEC technology under examination and the safety strategy adapted. These MCLs should be sufficient to demonstrate the required MEC's stability and reliability, which should have been already proven in model simulation calculations carried out in the preliminary phases of the device. Moreover, simulation models should be validated against these tests and relative measurements, so that simulation calculations could be performed to determine ultimate and fatigue limit states. The method to classify measured time histories is described, and more detailed information on MLCs for MECs with blades connected to a rotor shaft are given. The quantities that need to be measured in order to perform a correct comparison between measured and simulated load values are presented.

Moreover, the technology and instrumentation that should be used to measure the loads experienced by the system or sub-component are discussed. Considerations on the type of sensor, its location, PTO and station keeping loads measurement, are made. In order to ensure measurement accuracy, calibration methods and factors are provided. Moreover, to assure that signals are being measured correctly and to exclude errors in the recording phases, data verification methods are presented. The topic of processing of measured data and relative requirements is also covered, focusing on time series analysis, summary load statistics, load spectra and estimation of equivalent loads.

Finally, uncertainties evaluation and estimation in the measurement are discussed, and information on the results of the mechanical loads tests that should be included in a report are listed.

3.5.3 TS4: Standard for establishing qualification of new technology (proposed stability date 2021) [12]

The technology qualification process is of fundamental importance in the development of new, unproven technologies. The aim of this process is to prove and ensure that the technology under examination respects a reliability level for a certain operating environment with an associate acceptable level of confidence. The scope of this document is to support the technology qualification process, providing practices and technical requirements to comply with the IECRE certification process for marine renewable energy systems. Starting from a general description of the technology qualification process, the document provides guidance through its phases, from preparation of qualification basis and system decomposition to risk assessment and development of technology qualification plan, which consolidates the results of the study. A list of elements that should be included in the report of the technology qualification plan is given.

3.5.4 TS103: Best practices and recommended procedures for the testing of pre-prototype devices (proposed stability date 2022) [13]

The scope of this technical specification is to describe best practices and procedures to develop a test program that will form the basis of a structured technology development schedule. It covers both controlled environment test programs such as wave tank tests, and large-scale sea trials where environmental conditions cannot be scheduled and test programs need to be adjusted to the environmental conditions. This document defines prerequisites, targets and minimum tests plans that should be considered in each testing campaign. However, it is underlined that due to possible differences between the types of WEC under development, test facilities and instrumentation, each model test program should be customized in order to meet the specific design requirements. This document should serve as guide around with the model test campaign is defined to comply with the basic design requirements.

First a general overview of the development process, which is divided in 5 stages, from the early stage of the design to the final commercial unit, is given. A Technology Readiness Level (TRL) is associated to each stage, and also specific design objectives that the device needs to achieve in order to advance to the next stage. This TS guides wave energy stakeholders in the development of the device from stage 1 (TRL 1) to stage 3 (TRL 6). In stage 4 and 5 full-scale testing programs are carried out and this topic is not covered by this document.

Test planning considerations that should be made before each stage are discussed. More in detail, this TS provides recommendations and descriptions on the stage's scopes and gates. Then, indications, issues and good practices that should be taken into account to scale the WEC are presented. The design statement for the laboratory testing programs of each stage is discussed, listing the elements that it shall, should, or may be included. Consideration on the physical characteristics that the model should present, together with minimum requirements that should be considered in the selection of the test facility and site, are provided. Recommendations on the reporting of test planning considerations, results and performance indicators are given. Then, the document moves to the topic of testing environment characterization process, indicating methodologies that should be adopted in wave tank tests and sea trials. It also covers the aspects of data acquisition, it provides guidelines that should be followed in each development stage for the correct estimation of the power performance, device loads, motions and seaworthiness, in both operational and survival conditions.

3.6 Standards from relevant sectors

This sub-section introduces an analysis of standards and regulations from other industries (i.e., Oil and Gas, Offshore wind etc.) that, in some specific and detailed parts, can be applied to WECs.

3.6.1 GL Rules and Guidelines IV-6-4 (2007) Rules for Classification and Construction IV Industrial Services [6]

This guideline is divided into 10 main sections which cover the fundamental aspects of the structural design of offshore technologies. It provides descriptions of the typical environmental conditions that marine system will be facing (e.g. wind, sea current and waves), guidance on the estimations of resulting loads and principles for structural design of offshore installations. Steel and concrete materials and structures together with their properties are presented and described. The corrosion problem and relative protection is investigated. One section is dedicated to foundations of fixed offshore structures and covers piled as well as gravity type design. Information on cranes, cranes pedestal and crane lashing equipment including their foundation and substructures is given. Last sections are dedicated to helicopter landing facilities and general marine operations.

The engineering principles and formulations presented in this document can be applied to all offshore technologies, including WEC systems, with relative limitations and considerations on the necessary safety level required. In particular, the first sections that cover environmental conditions, loads and principles of structural design, it adapts well to WEC's technologies, without the need for modifications.

3.6.2 GL Rules and Guidelines IV-2-5 (2012) Guideline for the Certification of Offshore Wind Turbines [7]

This guideline applies to the design, assessment and certification of offshore wind turbines, focusing on the structural design and strength analysis. Chapter 10 can be useful for the scope of this project since it covers the aspects of testing at the prototype level. General indications and requirements on tests procedures at this stage of the design are given. Moreover, the document focuses on the estimation of power performances, noise emission, electrical characteristics, and load measurement of wind turbines. The topic of gearboxes prototype testing is also discussed.

3.6.3 DNVGL-ST-0119 (2018) Floating Wind Turbine Structures [8]

This document is focused on the structural design of offshore floating wind turbines. Principles, technical requirements and guidance for the design, construction and in-service inspection are provided. When possible, references to the requirements established in DNVGL-ST-0126 are made.

The standard firstly discusses about the safety philosophy and design principles of offshore floating wind turbines. This introduction is made considering that design requirements and safety factors employed in the design of floating structures depend on the relative consequence class, which is defined by the failure consequences of the device. For each consequence class, a target safety level can be achieved. Floating wind turbine structures are comparable to WEC in terms of safety class, since they are both unmanned, and the failure consequences are limited to the financial aspect. For this reason, the considerations reported in this document, especially on this topic, are well applicable to the WEC sector. The standard gives indications on the evaluation of the environmental conditions, loads estimation and load effects, which will be used to perform the strength analysis of the device. Materials specifications and the requirements for structural design of hull, mooring lines, tendons, anchors, and station keeping systems are given.

The standard describes the procedure to determine load effects, structural resistance and material degradation through testing of full-scale structures.

Moreover, it also covers the aspects of floating stability, control system, mechanical and electrical systems, corrosion protection, transportation and installation, in-service inspection, maintenance, monitoring and power cable design.

4 Gap analysis and roadmap towards exploitation

Currently, there are many different typologies of WECs that harvest energy from marine waves, each of them working with different principles and technologies. This aspect, combined with the high complexity of the marine environment in which they operate, tends to complicate the process of standardization, especially in the testing field.

From the desktop study carried out in this deliverable, it is clear that in the last decade the main players and stakeholders of the marine energy converter sector have worked towards the direction of standardization of norms and regulations. These efforts have been made with the scope of facilitating the industrialization of these devices, lowering design uncertainties, and raising the TRL. This type of study has been already undertaken in several projects in the past. For instance, in the MaRINET2[1] project (2017/2018) a similar gap analysis was carried out, in order to accelerate the development of wave, tidal and offshore wind energy technologies by opening up access to 57 test facilities across 13 European country. From the outcomes of this project, the topics and areas that need to be implemented or are not well covered from existing WEC standards are:

- A methodology to scale, model and test the power take-off system;
- The mooring system design;
- Failure due to effects of fatigue stresses and corrosion;
- The effects of marine growth on WECs' integrity and power performance.

Comparing the most relevant existing norms and regulations presented in Section 3 and using the outcome of the MaRINET2[1] project as a starting point, a gap analysis has been performed highlighting potential lacks and weaker areas of existing regulations. Moreover, due to the nature of the VALID project, the analysis focuses on the lacks in testing procedures. The main areas identified are presented in the next sub-sections, with a brief description of the topics and where the main gaps lie.

4.1 Full-scale testing

The TS IEC62600-103 [13] discusses and presents guidance on physical model tests for the WEC sector, outlining scopes and objectives that should be achieved in model tests in order to advance to the next stage of the development. The document focuses on the early stages of the design, from the concept model to the design model and subsystem model, or more in particular from TRL 1 to 6. In these stages of the design (from stage 1 to 3) the tests are typically performed at model scale. However, there are no standardised procedures that cover higher stages of the design, at which full-scale tests should be carried out. Gaps are identified in the scaling procedure from models to real size prototypes, progression from tank tests to real ocean environment and identification of prerequisites, goals, and test plans for full-scale prototypes.

4.2 Mooring system

The mooring system is a key component in the design of a WEC, both in terms of costs and influence on the power performance of the device. The mooring system, in the Oil & Gas industry, is typically designed to minimize platform motions. On the other hand, most WECs take advantage of their motion to harvest energy from sea waves. For this reason, there is an increase in application of relatively new synthetic mooring lines materials, such as polyester and nylon which allow greater platform motions and consequently enable to increase the power

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[1] https://www.marinet2.eu/

absorption of the device. However, there is still a limited amount of data and experience regarding these materials as well as standardised procedures that can be followed to perform valid and uniform rope tests. This problem is also related to general difficulties in accessing to rope testing facilities.

Another aspect that should be considered when dealing with these synthetic materials is the effects of dynamic stiffness on the mooring tensions and system's response. Indeed, most of the existing design procedures uses quasi-static stiffness models which tends to underestimate maximum mooring tensions [14]. Design procedures that take into account these dynamic stiffness effects are still extremely time and computational demanding.

Moreover, most WECs work close to their resonance frequencies in order to maximize their power performance. This will induce high frequency loads to the mooring lines, that can lead to unpredicted failure of the mooring system and consequently, to a possible loss or breakdown of the device. Existing guidelines do not include dynamic tests to evaluate the effects of this type of loads on the mooring system.

The lack of procedures, knowledge and experience lead to uncertainties in the strength and resistance of the mooring system which implies high safety factors and consequently, high materials' costs. At the same time, current guidance does not provide a certification process to evaluate case by case the necessity of this conservative requirements.

4.3 Marine environment

WECs are designed to operate in a marine environment characterized by high complexity in its prediction and modelling. Indeed, marine loads come from multiple dynamic sources, such as waves, wind, currents and tide, which are difficult to reproduce in model scale testing. Existing regulations estimate these loads with simplified characterization of the environmental conditions. There are no procedures that foresee tests with site specific wave spectrum (non-parametric), multi-modal sea states, shallow water breaking waves and consequent effects on the structure of the device. Moreover, tidal current, and the interaction effects between waves and current seem to have a significative impact on the power performance of WECs and this is not addressed in any guidance.

The marine environment is highly corrosive, and this natural process can be extremely impacting on the durability and power performance of the device over its service life. However, there is a gap in existing standards regarding this issue since no material testing procedures are defined to understand failure cases due to corrosion and combined effects of fatigue and corrosion.

Another gap in WEC regulations is the analysis of marine growth on devices and mooring systems. There are existing documents that cover this issue; however, they are related to other marine industries, and they are not directly applicable to WECs. The effects of marine growth on the power performance, survivability, durability, structure resistance of the device and degradation of ropes should be considered from future standards in order to allow the industry stakeholders to perform more precise estimations on the feasibility of a specific WEC project.

4.4 PTO

In D1.1, an industrial survey was conducted involving experts and stakeholders of the marine energy sector, with the scope of understanding which are the main issues and the most followed standards, guidelines, and technical specifications for testing WEC components. From this survey, it was found that the PTO is the most critical WEC sub-system component. This outcome is directly related to the various gaps that can be found in existing regulations of testing procedures for the PTO sub-system, as it was already defined in the MaRINET2[1] project. The main lacks can be identified in guidance on the scaling process of the PTO, in testing procedure for scaled WECs with pneumatic or compressible PTOs, and its performance prediction and assessment.

5 Conclusion

The study carried out in this project has demonstrated that there is already a large number of regulations and standards on WEC technologies and also specifically dedicated to the testing topic. At the same time, the gap analysis presented has identified which areas and topics of regulations and standards should be implemented in order to reach that standardization level, facilitating the development and the industrialization of these technologies. The main regulations' gaps identified regard the topics of:

- Full-scale testing;
- Mooring system;
- Marine environment;
- PTO.

A first step in the direction of improving standards and guidelines related to WECs' technology could be made drawing on the experience gained from the various stakeholders that are taking part in this project. Particularly, using the gap analysis carried out in this derivable as a starting point, it could be possible to understand which areas of existing regulations are well covered and which need to be reviewed or implemented.

Once gaps and bottlenecks aspects for the standardisation of these technologies have been identified, inputs and ideas from the various players of this project should be collected in order to produce a step towards this standardisation process. Moreover, the three use cases analysed in WP3, WP4 and WP5 will serve to prove the validity of this new technical specifications.

6 Nomenclature

Abbreviations

DLC	Design Load Case
DNV	Det Norske Veritas
EC	European Commission
EMEC	European Marine Energy Centre
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
H2020	Horizon 2020
IEC	International Electrotechnical Commission
LCC	Life Cycle Cost
MEC	Marine Energy Converters
MCL	Measured Load Cases
OES	Ocean Energy System
PTO	Power Take-Off
RES	Renewable Energy Source
TRL	Technology Readiness Level
TS	Technical Specification
WEC	Wave Energy Converter
WP	Work Package

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