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Collaborative project

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Lead author:	K2M / Laporte Weywada, Pauline
Author	K2M / Scriven, Joshua
Author	K2M / Cruz, Joao
Author	AWE / Jarno Hakulinen
Author	AWE / Jussi Åkerberg

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Verified (Sc Coordinator)	Jussi Åkerberg (AWE)	2019-04-30
Approved (Coordinator)	Ilpo Honkanen (Hydroll)	2019-04-30

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EXECUTIVE SUMMARY

To facilitate the development of the wave energy converter (WEC) industry, a considerable effort needs to be conducted to establish appropriate international guidelines that can reduce uncertainties, standardise e.g. design or manufacturing approaches, and streamline the accreditation process up to commercial arrays.

The marine energy industry is still at its infancy, and no dedicated standards have been developed to date. Recently, a number of high-level documents that have approached WEC design and certification have been developed, in particular technical specifications e.g. from the IEC TC114 group. Moreover, more mature industries such as the maritime, oil and gas and offshore wind sectors present similarities to some aspects of the marine renewable energy sector, in aspects such as e.g. design of marine structures. A range of key documentation from such industries has therefore been used to date to support the development of WEC devices.

As part of the MegaRoller project, one of the key objectives is to monitor the development of technical specifications, guidelines and standards relevant to the WEC industry, and in particular to the MegaRoller technology. Such monitoring aims to guide the design, implementation and integration of the Power Take-Off (PTO) and thereby facilitating its commercialisation. In a preliminary step, this report reviews existing standards and their applicability, and documents an analysis related to the existing documentation. The objective is to identify any salient gaps and to ensure the appropriate applicability of relevant design codes during the project.

Overall, the review evidenced two essential differences between WECs and other, more mature offshore applications:

1. Being (in general) unmanned structures, the safety factors of WECs associated with a specific failure could potentially be lower than the ones currently recommended in the standards, as the consequence of failure may be considered less critical when compared to equivalent failure in a manned structure.
2. WEC subsystems may be subject to different loads, which may require consideration of specific dominant failure modes. For example, design for near resonance can led to fatigue becoming a governing failure mechanism, which in turn affects WEC reliability.

The high-level gap analysis provided in this report can be considered a starting point for further standardisation work, highlighting some of the key issues that should be addressed to facilitate the design and development of the emerging WEC industry. As the MegaRoller project progresses, a continuous monitoring of the ongoing standardisation effort will be performed, assessing the relevance and applicability of the specifications and guidelines to the MegaRoller project and to the WEC industry. A range of dissemination activities is also expected to contribute to informing the standard requirements, via workshops with the stakeholders of the industry, or presentations at relevant conferences or relevant events (e.g. webinars, brokerage events, seminars). Overall, the final key findings regarding the applicability of technical specifications, guidelines and standards to the MegaRoller technology (and the WEC industry in general) will be documented at the completion of the project. The final report will constitute an extension of the present document, providing a view of the most up-to-date status of the standardisation work, along with clear recommendations for the future activities.

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List of Acronyms

ADC	Analogue-to-digital
API	American Petroleum Institute
BS	British standard
DAQ	The Data Acquisition
DNV	Det Norske Veritas
DNV-GL	Det Norske Veritas - Germanischer Lloyd
EMEC	European Marine Energy Centre
EN	European Standard
HMI	Human Machine Interface System
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LRFD	Load and Resistance Factor Design
NORSOK	Norsk Sokkels Konkuranseposisjon
O&M	Operation and maintenance
PTO	Power Take-Off
SDWED	Structural Design of Wave Energy Devices
SOLAS	International Convention for the Safety of Life at Sea
WEC	Wave Energy Converter

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1 INTRODUCTION

1.1 Scope of the Document

To facilitate the development of the wave energy converter (WEC) industry, a considerable effort needs to be conducted to establish appropriate international guidelines that can reduce uncertainties, standardise e.g. design or manufacturing approaches and streamline the accreditation process up to commercial arrays.

The marine energy industry is still at its infancy, and no dedicated standards have been developed to date. Recently, a number of high-level documents that have approached WEC design and certification have been developed, in particular technical specifications e.g. from the IEC TC114 group. Moreover, more mature industries such as the maritime, oil and gas and offshore wind sectors present similarities to some aspects of the marine renewable energy sector, in aspects such as e.g. structural design of marine structures. A range of key documentation from such industries has been used to date to support the development of WEC devices.

As part of the MegaRoller project, one of the key objectives is to monitor the development of technical specifications, guidelines and standards relevant to the WEC industry, and in particular to the MegaRoller technology. Such monitoring aims to guide the design, implementation and integration of the Power Take-Off (PTO), facilitating its commercialisation. In a preliminary step, this report reviews existing standards and their applicability, and documents a gap analysis related to the existing documentation, aiming to identify any salient gaps and to ensure the appropriate applicability of relevant design codes during the project.

This report is organised in three main sections. Following this introduction (Section 1), a review of existing relevant standards and their applicability to both the MegaRoller project and the WEC industry in general is provided in Section 2. To conduct the review, the WEC system was broken down into key subsystems. A high-level technology assessment is conducted for each key subsystem, assessing the novel aspects and reviewing existing documentation covering relevant lifetime aspects. A gap analysis is then documented in Section 3, considering the lifetime aspects covered by the reviewed standards and the project / industry requirements. The next steps for the MegaRoller standardisation activities to be conducted under Task 6.6 are then recommended in Section 3.

1.2 Acceptance Criteria

This document adheres to the description of the deliverable provided in the Grant Agreement [GA, 2018]:

- "*D6.6 describes the existing standards and their applicability. It also includes a matrix that clearly describes what WEC lifetime aspect is covered by standards and what is missing in the standards*".

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2 EXISTING CODES AND STANDARDS

2.1 Overview

Technical specifications, guidelines and standards are essential to support the development of a specific industry. Standards (and codes, when adopted by governmental bodies) constitute a globally accepted set of technical definitions and instructions published by a recognised body. Technical specifications, on the other hand, constitute recommended requirements or guidelines on e.g. materials, components or services. Typically, technical specifications can be transformed into international standards when the technology is mature enough and an international consensus can be reached.

At present, there are no specific standards dedicated to the WEC industry, covering e.g. the design, manufacturing, commissioning and / or O&M stages. Recently, multiple high-level documents that have approached WEC design and certification have been developed, including:

i. Det Norske Veritas AS (DNV) Offshore Service Specification (OSS) 312 (DNV-OSS-312, October 2008). Provides an overview the principles and procedures associated with the certification of WECs. It does not include technical provisions [DNV GL, 2008].
ii. DNV's '*Guidelines on Design and Operation of Wave Energy Converters*', May 2005, The Carbon Trust. This document compiles a list of related standards and outlines methodologies for fatigue analysis (Appendix A) and wave load modelling (Appendix B). [DNV, 2005].
iii. The European Marine Energy Centre (EMEC) '*Guidelines for Design Basis of Marine Energy Conversion Systems*', 2009. Provides an overview of general aspects behind design basis documentation, covering both wave and tidal energy converters. [EMEC, 2009].
iv. The IEC TC114 group has issued a number of technical specifications that can be used to standardise the WEC design approach, such as:
    - IEC TS 62600-100:2012 - Electricity producing wave energy converters - *Power performance assessment* [IEC TS 62600-100:2012]
    - IEC/TS 62600-2 - Electricity producing wave energy converters - *Design requirements for marine energy systems* [IEC TS 62600-2]

Furthermore, key documentation from the maritime, oil & gas and offshore wind sectors may be potentially relevant to WEC design, primarily due to the extent of the similarities in the structural design of these structures.

At a high-level, a WEC system can be broken down into the following key subsystems [SDWED, 2014] – see also Figure 2.1:

- A hydrodynamic subsystem, that captures the wave power in an efficient manner.
- A reaction subsystem, that maintains the position of the WEC and transfers the loads to the seabed.
- A PTO subsystem, that converts the captured wave power into grid-quality electric power.
- A control subsystem and instrumentation, that measures target variables and controls the device.
- An electrical generation and power transmission subsystem, that transfers the electrical power.
- An interface subsystem, where the different WEC subsystem blocks interact with the others.

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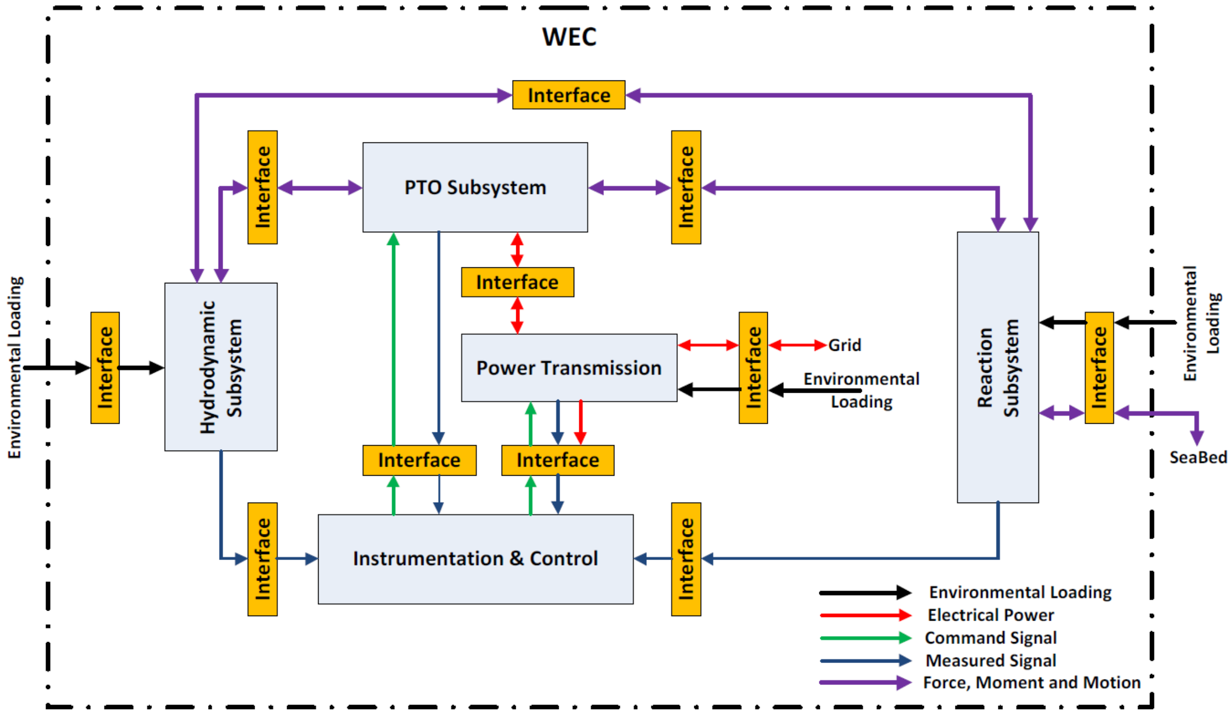

Figure 2.1 Typical WEC block diagram with key subsystems [SDWED, 2014]

In this section, a review of the guidelines, codes or standards relevant to the design of each key WEC subsystem is provided – see Sections 2.2 to 2.7. The review is guided by the risk ranking and failure mode approach described in [SDWED, 2014], quantifying the risks in the design of WECs to prioritise the standardisation activities required. A technology assessment is conducted for each subsystem, where novelties are quantified according to [DNV GL, 2008], based on the following categories:

1. No new technical uncertainty (proven technology for a known application area, covered by comprehensive standards).
2. New technical uncertainty.
3. New technical challenge.
4. Demanding and new technical challenge (new or unproven technology for a new application area).

Finally, existing standards relevant to other WEC lifetime aspects are covered in Section 2.8.

2.2 Hydrodynamic Subsystem

Following the WEC breakdown proposed in [SDWED, 2014], the main function of the hydrodynamic subsystem is to capture the wave power in an efficient manner. The hydrodynamic subsystem is also designed to transfer motions and forces to both the reaction and PTO subsystems (see Sections 2.3 and 2.4, respectively).

To date, a range of hydrodynamic subsystems have been developed to address these functions. Typically, four main categories of hydrodynamic subsystem can be conceived [SDWED, 2014]: oscillating body, oscillating water column, overtopping device and diaphragm pressure differential. The MegaRoller WEC falls under the first of these categories (oscillating body, using the pitching degree-of-freedom).

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From the technology assessment point of view, rigid offshore structures using known materials and known manufacturing processes are ranked as a Class 2 technology [SDWED, 2014], i.e. proven technology with a new application, supported by a range of standards from the maritime, oil & gas and offshore wind sectors. Table 2.1 provides a shortlist of key documentation that are potentially relevant to the structural design of an oscillating WEC rigid hydrodynamic subsystem.

Table 2.1 Core documentation: Hydrodynamic subsystem

Doc. Reference	Application / Relevance	Supporting / Additional Documents
DNVGL-ST-C501 (2017) Composite Components. DNVGL-OS-C101 (2018) Design of offshore steel structures, general – LRFD method.	Structural design and analysis (primary composite and steel design, respectively). Strength analysis in FEM.	GL Rules and Guidelines IV-6-4 (2007) Offshore Technology - Structural Design. GL Rules and Guidelines IV-2-5 (2012) Guideline for the Certification of Offshore Wind Turbines - Strength Analyses. DNVGL-RU-SHIP-Pt2Ch3 (2015) Materials and Welding – Non-Metallic Materials. DNVGL-RU-SHIP-Pt2Ch2 (2018) Materials and Welding – Metallic Materials.
DNVGL-RP-C205 (2017) Environmental Conditions and Environmental Loads.	Overall description of environmental conditions and design loads (environmental, permanent, functional and accidental), including principles for structural design.	DNVGL-OS-C103 (2015) – Amended 2018 (replaced DNV-OS-C103) Structural Design of Column Stabilised Units (LRFD Method). DNVGL-RP-C204 (2017) Design against Accidental Loads. API RP 2FPS (2011) Recommended Practice for Planning, Designing, and Constructing Floating Production Systems.
ABS Pub# 115 (2018) Guide for Fatigue Assessment of Offshore Structures. DNVGL-RP-C203 (2016) Fatigue Design of Offshore Steel Structures.	Overview of fatigue assessment methods in offshore installations (inc. safety factors).	DNVGL-CG-0129 (2018) Fatigue Assessment of Ship Structures DNVGL-OS-C102 (2018) Structural design of offshore ship-shaped units
DNV-RP-A201 (2014) Document Types – Definitions.	Quantitative reliability assessment.	API RP 17N (2017), Recommended Practice for Subsea Production System reliability and Technical Risk Management. BS 5760 (2014) Reliability of systems, equipment and components. ISO 14224 (2016) Collection and exchange of reliability and maintenance data for equipment. ISO 2394 (2015) General Principles on Reliability for Structures.
DNVGL-OS-C401 (2018 – Amended 2019) Fabrication and testing of offshore structures.	Manufacturing and testing, for example leakage tests.	DNVGL-CG-0051 (2015) Non-destructive testing. DNVGL-CP-0069 (2016) Welding consumables.

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The structural design of offshore technologies (e.g. offshore wind) follows standard methods such as the Load and Resistance Factor Design (LRFD) approach. In this method, partial safety factors are assigned to address uncertainty in the loads (due to e.g. temporal variability) and resistance (due to e.g. material strength properties). For steel structures, the following factors are defined in DNVGL-OS-C101:

a. Partial load effect factors (γ_F), which are applicable to the characteristic values in order to account for uncertainties on the loads applied to the structure.
b. Partial resistance factors (γ_M), which aim to account for uncertainties associated with the variability of the strength.

Other factors may also be defined, for example resistance model factors (γ_{Rd}) for composite materials where the structural failure modes are subject to larger uncertainties when compared with steel.

Overall, a general inequality determines if the structural reliability can be considered satisfactory, given by:

$$\gamma_F S_k \leq \frac{R_k}{\gamma_M},$$

where S_k is the characteristic load effect and R_k is the characteristic resistance. The characteristic load effect S_k is a value that rarely should be exceeded. For time dependent processes, it is usually related to a long-term return period.

Alternatively, a probability-based approach may be taken, where each variable is assigned a statistical distribution and a target probability of failure is selected according to the consequence of the failure. This approach can give more detailed insight into the probability of failure and the relative effect of each uncertainty, but remains atypical in (conventional) offshore design.

Although the design of hydrodynamic subsystems can be supported by a wide range of existing standards from other industries, the interaction with the PTO subsystem is typically not considered. For example, the LRFD method in DNVGL-OS-C101 assumes that the load component can be broken down between permanent loads, variable functional loads, environmental loads, accidental loads and deformation loads. PTO loads may fall under the variable functional load category, as loads which may vary during the normal operation conditions, or under environmental loads category, as loads significantly correlated with the environmental conditions. Furthermore, specific requirements may be associated with such loads, e.g. such as those associated with the functional loads on deck areas shown in Table 3 of DNVGL-OS-C101. In particular, considering the reduced risk for both human life and the environment compared to e.g. oil & gas structures, [DNV, 2005] suggests using lower load factors for environmental loads that those recommended in Table 1 of DNVGL-OS-C101. This highlights that significant revisions of the relevant standard(s), or a new standard dedicated to the design of WEC structures, may be required to ensure its direct applicability to the design of WEC hydrodynamic subsystems (see also Section 3).

2.3 Reaction Subsystem

The main function of the reaction subsystem is to maintain the position of the WEC and to transfer the loads to the seabed [SDWED, 2014]. In the case of the MegaRoller, the hydrodynamic subsystem (the panel) is rigidly attached to the seabed via a gravity-based foundation.

From a technology assessment perspective, reaction subsystems rigidly fixed to the seabed using known materials and known manufacturing processes are ranked as a Class 2 technology [SDWED, 2014], i.e. proven technology with a new application, supported by a range of standards from the maritime, oil &

gas and offshore wind sectors. Table 2.2 provides a shortlist of key documentation that are potentially relevant to the structural design of reaction subsystem rigidly fixed to the seabed.

Table 2.2 Core documentation: Reaction subsystem

Doc. Reference	Application / Relevance	Supporting / Additional Documents
DNVGL-ST-0126 (2016) Support structures for wind turbines. DNVGL-ST-C502 (2018) Offshore concrete structures	Description of design approaches for design of foundations including gravity-based concrete foundations. Requirements to materials, execution and O&M related to the design.	DNVGL-RP-C212 (2017) Offshore soil mechanics and geotechnical engineering. DNVGL-RP-C207 (2017) Statistical Representation of Soil Data. BS EN ISO 19901-8:2015 Specific Requirements for Offshore Structures – Part 8: Marine Soil Investigation.
DNVGL-OS-C401 (2018 – Amended 2019) Fabrication and testing of offshore structures.	Manufacturing and testing, for example leakage tests.	BS EN 10080:2005 Steel for the reinforcement of concrete - Weldable reinforcing steel – General. EN 12390 Testing hardened concrete.
API Recommended Practice 2A-WSD (2014) Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design.	Design and construction of fixed offshore platforms. The WSD method is mainly applicable to reinforced concrete design.	-

When considering the design of the reaction subsystem, a similar approach to that described in Section 2.2 for the structural design of offshore technologies is proposed in e.g. DNVGL-ST-0126, establishing the design load effect(s) associated with a particular load source(s). However, and as stated in Section 2.2, the interaction with the PTO system is typically not considered. To address this gap, significant revision of the relevant standard(s), or a new standard dedicated to the design of WEC structures, may be required (see also Section 3).

2.4 PTO Subsystem

The PTO converts the captured wave power into grid-quality electric power by transferring the motions and forces of the hydrodynamic subsystem to the generator shaft [SDWED, 2014]. The MegaRoller PTO can be categorised as a hydraulic system, where the cyclic motion of the hydrodynamic subsystem causes the linear actuator (i.e. the hydraulic cylinder) to move back and forth. The reciprocating motion of the actuator pumps the fluid through the hydraulic system, and a specific arrangement of valves and accumulators controls and diverts the fluid to the hydraulic motor. The hydraulic motor then rotates the generator shaft.

A hydraulic system typically consists of the following key components:

- Valves, that control the flow, pressure and direction.
- Motors, that convert the fluid power to linear or rotary mechanical motion.
- Pumps and cylinders, that convert the rotary or linear mechanical power to fluid power.
- Fluid conditioning, that condition the fluid characteristics (e.g. filters, heaters…).
- Fluid connectors, that connect the different fluid components (e.g. pipe, manifold…).
- Accumulators, that store the potential fluid power.
- Hydraulic fluid, that can be water-based or oil-based.

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The operation of the PTO also depends on a number of auxiliary subsystems (e.g. brake / latch system, shock absorption system, heating / cooling system etc.), that aim to maintain the operational conditions for safe and reliable operation of the PTO.

In order to enhance the reliability, improve the ease of maintenance, increase the availability of spare parts, and reduce the costs of the MegaRoller system, the PTO is being designed using as much as possible off-the-shelf, standard components such as generators, hydraulic motors or hydraulic accumulators. The design and manufacturing of these components is extensively supported by recognised industry standards. Table 2.3 provides a shortlist of key documentation that are potentially relevant to the structural design of PTO subsystems, focusing on the assembly rather than on the component level.

Table 2.3 Core documentation: PTO subsystem

Doc. Reference	Application / Relevance	Supporting / Additional Documents
DNVGL-OS-C101 (2018) Design of offshore steel structures, general – LRFD method.	Strength analysis in FEM.	DNVGL-CG-0127 (2015- Amended 2016) Finite element analysis. DNVGL-RP-C203 (2016) Fatigue design of offshore steel structures. DNVGL-OS-D101 (2018) Machine and machinery systems and equipment.
PD 5500:2018+A1:2018 Specification for unfired fusion welded pressure vessels.	Design, construction, inspection and testing of unfired pressure vessels. Pressure containment of the hydraulic cylinders.	BS EN 13445 Unfired pressure vessels. BPVC-VIII-1 (2017) ASME's Boiler and Pressure Vessel Code Section VII – Rules for Construction of Pressure Vessels Division 1.
DNVGL-OS-C401 (2018 – Amended 2019) Fabrication and testing of offshore structures.	Manufacturing and testing, for example leakage tests.	ISO 4406:2017 Hydraulic fluid power - Fluids - Method for coding the level of contamination by solid particles.
ISO 12100:2010 Safety of machinery; General principles for design – Risk assessment and risk reduction. ISO 4413:2010 Hydraulic fluid power – General rules and safety requirements for system and their components. BS EN 764-7:2002 Pressure equipment. Part 7: Safety systems for unfired pressure equipment.	Machinery safety.	BS EN 60204-1:2018 Safety of machinery – Electrical equipment of machines – Part 1: General requirements. ISO 4126-1:2013 Safety devices for protection against excessive pressure – Part 1: Safety valves.

Overall, the PTO subsystem is relatively well covered at component-level by recognised, international standards. Although a hydraulic PTO technology is relatively standard, its specific application to WEC systems may involve a range of potentially new aspects, related e.g.:

- The interaction with a complex control subsystem.
- The characteristics of the mechanical loading on the hydraulic actuators.
- The characteristics of the electrical loading on the high-power drive for controlling the generators.
- The fatigue life of the dynamic seals, in face of the loading conditions.
- The maintenance regime.

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From the technology assessment point of view, such novelties lead to a Class of hydraulic PTO systems ranked between 2 and 4 [SDWED, 2014], i.e. new application of a potentially new technology. This may require the revision of existing gaps to cover the new aspects in the proposed application (see also Section 3).

It should be noted that, with regard to the specific case of the MegaRoller hydraulic PTO subsystem, the novelty aspect in the above listed points remains fairly limited, in particular when considering that the control system is limited to a damping control strategy, and that hydraulic accumulators limit the fluctuation in the generator speed. Therefore, no specific gaps have yet been identified; however, such assessment may evolve as the MegaRoller PTO design progresses from a concept phase to a more detailed design stage.

2.5 Instrumentation and Control Subsystems

The main function of the instrumentation and control subsystems is to measure target variables and control the device [SDWED, 2014]. The main components include:

- Sensors (monitoring sensors, alarm sensors and control sensors), that measure the target parameters and data across the different systems.
- The Data Acquisition (DAQ) system, that conditions the raw signal, converts the signals from analogue to digital (ADC) and stores the relevant data.
- Processors that manipulate the digital or analogue signals.
- The communication and data transfer system, that can be wireless system (e.g. via radio, cellular, Wi-Fi, sonar or satellite) or through wire (fibre optic cable, Ethernet cable).
- The Human Machine Interface System (HMI), that handles the human interaction with the machine (e.g. screens, monitors, switches and joysticks).

Essentially, the instrumentation and control subsystems aim at monitoring and controlling the conditions in which the device operates. The design of this subsystem should consider the reliability and performance targets for WEC (e.g. required design life, criticality of the component, maintenance strategy etc.). Typically, the instrumentation and control subsystems aim at monitoring parameters such as accelerations, pressures, loads, vibrations, temperature, humidity, electromagnetic interferences etc. Table 2.4 provides a shortlist of key documentation that are potentially relevant to the design of the instrumentation and control subsystems.

Overall, the requirements of instrumentation and control systems addressed in most of the standards listed in Table 2.4 were initially dedicated to maritime and oil & gas industries, on the basis of manned installations. When considering the specific requirements for WEC devices, some adjustments may be required, e.g. with respect to operator interface and maintenance issues (see Section 3).

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Table 2.4 Core documentation: Instrumentation and control subsystems

Doc. Reference	Application / Relevance	Supporting / Additional Documents
IEC 61131-2:2017 Industrial-process measurement and control - Programmable controllers - Part 2: Equipment requirements and tests.	Functional and electromagnetic compatibility requirements of industrial control equipment.	IEC 60533:2015 RLV Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull. IEC TR 61000-4-1:2016 Electromagnetic compatibility (EMC) - Part 4-1: Testing and measurement techniques - Overview of IEC 61000-4 series.
IEC 60870-5 Series Telecontrol equipment and systems – Transmission protocols.	Systems used for telecontrol (Supervisory Control and Data Acquisition). Defines the operating conditions, electrical interfaces, performance requirements and data transmission protocols for local and remote supervision and control.	IEC 61400-13:2015 Wind turbines - Part 13: Measurement of mechanical loads. IEC 61400-25-1:2017 RLV Wind energy generation systems - Part 25-1: Communications for monitoring and control of wind power plants - Overall description of principles and models.
ISO 13849-1:2015 Safety-related parts of control system – Part 1: General principles for design.	Safety requirements and guidance on the principles for the design and integration of safety-related parts of control systems.	ISO 12100:2010 Safety of machinery - General principles for design - Risk assessment and risk reduction. IEC 62061:2005 + AMD1:2012 + AMD2:2015 CSV Safety of machinery – Functional safety of safety–related electrical, electronic and programmable electronic control systems.
DNVGL-OS-D202 (2017) Automation, safety and telecommunication systems.	General requirements to safety, telecommunication and automation systems. Applies to mobile offshore units.	DNVGL-OS-D201 (2017 – Amended 2018) Electrical installations. DNVGL-CG-0339 (2016) Environmental test specification for electrical, electronic and programmable equipment and systems.
ISO 17359:2018 Condition monitoring and diagnostics of machines – general guidelines.	General procedures to be considered when setting up a condition monitoring programme for machines.	ISO 13379-1:2012 Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines.
DNVGL-OS-A101 (2017 – Amended 2018) Safety principles and arrangements.	Requirements for shut down logic, alarms, escape ways and communication.	DNVGL-OS-D202 (2017) Automation, safety and telecommunication systems. DNVGL-OS-D301 (2017) Fire protection.
IEC 61850:2019 SER (series) Communication networks and systems for power utility automation - ALL PARTS.	Communication protocols at electrical substations.	-

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2.6 Electrical Generation and Power Transmission Subsystem

The main function of the power transmission subsystem is to transfer the electrical power in an efficient and reliable manner from the WEC until the grid (or the consumption source) [SDWED, 2014]. Typically, it consists of a high-power electrical equipment such as generators, transformers, switchboards, switchgears, connectors and power cables.

Table 2.5 provides a shortlist of key documentation from these sectors that are potentially relevant to the design of the electrical generation and power transmission subsystems.

Table 2.5 Core documentation: Electrical generation and power transmission subsystems

Doc. Reference	Application / Relevance	Supporting / Additional Documents
IEC 60364 Low voltage electric installations.	Design, erection, and verification of low-voltage electrical installations.	IEC 61439-1:2011 Low voltage switchgear and control gear assemblies - Part 1: General rules.
IEC 61936-1:2010 + AMD1:2014 CSV Power installations exceeding 1kV a.c.	Design and erection of electrical power installations in systems with nominal voltages above 1kV a.c.	BS EN 50522:2010 Earthing of power installations exceeding 1kV a.c.
BS EN 50110-1:2013 Operation of electrical installations – Part 1: General requirements.	Operation of and work activity on, with, or near electrical Installations.	-
DNVGL-RP-0360 (2016) Subsea power cables in shallow water.	Design, manufacturing, installation, operation and maintenance of subsea cables.	ISO 13628-5:2009 Design and operation of subsea production systems - Part 5: Subsea umbilicals. BS EN 62230:2007+A1:2014 Electric cables. Spark-test method. ITU-T G.976 (2014) Test methods applicable to optical fibre submarine cable systems. DNVGL-ST-F201 (2018) Dynamic risers. IEC 60502-1:2004+AMD1:2009 Consolidated version API SPEC 17E (2017) Specifications for subsea umbilicals.
IEC TS 62600-30:2018 Wave, tidal and other water current converters - Part 30: Electrical power quality requirements.	Definition and specification of the quantities to be determined for characterizing the power quality of a marine energy converter unit; measurement procedures for quantifying the characteristics of a marine energy converter.	
DNVGL-ST-0125 (2016) Grid Code compliance.	Framework for proving grid code compliance by means of technical assessment, test, measurement, validation and simulation.	DNVGL-SE-0124 (2016) Certification of grid code compliance.

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In general, the connection arrangements involve a number of requirements in accordance with national grid codes that must be adhered to in order to gain permission for connecting the WEC power plant to the local electrical grid. As part of the MegaRoller project, the electrical design will aim to conform to specific grid codes of different market areas, following recommendations provided in DNVGL-ST-0125 (2016).

Overall, some of the codes and standards listed in Table 2.5 were designed for manned offshore installations. Revisions of these may be required to consider the operation of WEC devices under normal conditions, where the WEC is normally unmanned, to adjust items directly related to the safety of operating staff. For example, requirements for internal ambient conditions (e.g. minimal ventilation, removal of waste heat produced) could be reassessed to account for the unmanned conditions of operation.

2.7 Interface Subsystems

At a high level, the most common interfaces include [SDWED, 2014]:

- Interface between the environment and the target material (e.g. corrosion protections).
- Interface between components (e.g. seals).
- Interface between moving parts (e.g. bearings).
- Interface between subsystems (e.g. structural, mechanical or electrical connectors).

Most of these interfaces are considered as proven technologies with known application, i.e. Class 1 in the technology assessment, even in the context of WEC design. Table 2.1 provides a shortlist of key relevant documentation.

Overall, most of the interface subsystems are relatively well covered, with existing standards from other industries directly applicable to the WEC system. However, potentially new aspects may require the revision of some standards (see also Section 3), e.g. regarding the characteristics of the mechanical loading and the fatigue life of the bearings and seals, or regarding the subsea connectors.

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Table 2.6 Core documentation: Interface subsystem

Doc. Reference	Application / Relevance	Supporting / Additional Documents
NORSOK M-501 (2012) Surface Preparation and Protective Coating.	Requirements for the selection of coating materials, surface preparation, application procedures and inspection for protective coatings to be applied during the construction and installation of offshore installations and associated facilities. It covers paints, metallic coatings and application of spray-on passive fire protective coatings.	VGB-S-021-01-2018-04-EN (2018) Corrosion Protection for Offshore Wind Structures. NORSOK N-001 (2012) Integrity of offshore structures. DNVGL-RP-B401 (2017) Cathodic protection design. BS EN ISO 12944-5:2018 (2018) Paints and varnishes. Corrosion protection of steel structures by protective paint systems. Protective paint systems. DNVGL-RP-B101 (2019) Corrosion protection of floating production and storage units. DNVGL-OS-C101 (2018) Design of offshore steel structures, general – LRFD method.
NORSOK M-710 (2014) Qualification of non-metallic materials and manufacturers - Polymers	Applies for downhole, subsea and workover systems. It can be used for e.g. electrical isolation / sealing materials and sealing materials for hydraulic systems.	ISO 23936-1:2009 (2009) Non-metallic materials in contact with media related to oil and gas production. Part 1: Thermoplastics. ISO 10423:2009 (2009) Drilling and production equipment - Wellhead and christmas tree equipment.
IEC 61984:2008 (2008) Connectors – Safety requirements and tests.	Applies to connectors with rated voltages above 50V and up to 1000V a.c. and d.c. and rated currents up to 125A per contact.	-

2.8 Other Lifecycle Phases

In Sections 2.2 to 2.7, the review mostly focused on the design of the different subsystems considered. In addition to these aspects, other aspects such as marine operations, health and safety or environmental impact management are also essential in the WEC lifecycle [DNV, 2005]. These additional aspects have been the focus of a number of standards relevant to the maritime, oil & gas and offshore wind sectors. Table 2.7 provides a shortlist of key documentation from these sectors that are potentially relevant to the WEC industry.

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Table 2.7 Core documentation: Other lifecycle phases

Doc. Reference	Application / Relevance	Supporting / Additional Documents
ISO 45001:2018 Occupational health and safety management systems – Requirements.	Health and safety management of all operations.	International Convention for the Safety of Life at Sea (SOLAS 1974), especially chapter V Safety of Navigation.
DNVGL-ST-N001 (2018) Marine operations and marine warranty (replaces 0015/ND Rev 5.1 - 28 June 2016 - Guidelines for concrete gravity structure construction & installation).	Marine aspects of construction, towage and installation of offshore concrete Gravity Base Structures (GBS). Applicable to shallow draft structures where the construction of the GBS can be essentially completed in dry dock.	DNVGL-RP-N101 (2017) Risk management in marine and subsea operations. NORSOK Z-007 (2015) Mechanical Completion and Commissioning. ISO 19903:2006 Petroleum and natural gas industries — Fixed concrete offshore structures. DNVGL-ST-C502 (2018) Offshore Concrete Structures. DNVGL-RP-N102 (2017) Marine operations during removal of offshore installations
ISO 14001:2015 Environmental management systems.	Environmental management system.	-
IEC 60812:2018 Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA).	Failure mode, effects and criticality analysis (FMECA).	IEC 60050-192 International electrotechnical vocabulary – Part 192: Dependability.

Over the years, a significant standardisation effort has been conducted regarding the marine operation activities, drawn on the experience gathered from the maritime and oil & gas industries, and more recently from the offshore wind sector. However, some aspects more specific to the WEC requirements are not yet covered, such as the decommissioning of gravity-based structure (explicitly excluded from e.g. DNVGL-RP-N102 (2017) Marine operations during removal of offshore installations). Similarly, the operational safety of WEC's and the requirements that operational safety places on WEC control systems is not covered by current standards.

On the environmental aspects, the criteria for environmental risks are typically local-specific, where each community and stakeholder involved have different acceptance levels to the risk of environment impacts. Typically, and similar to other offshore development projects, an Environmental Impact Assessment (EIA) is generally required – where possible, some level of standardisation on the processes involved would be beneficial to streamline the development of the WEC industry, such as that initiated in PD 6900:2015 *Environmental impact assessment for offshore renewable energy projects – Guide*.

Overall, the specifics of WEC's and especially oscillating wave surge converter such as MegaRoller as underwater electricity-producing installations are not always covered by more general marine standards (see Section 3).

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3 KEY FINDINGS AND NEXT STEPS

3.1 Gap Analysis

The review of the existing codes and standards relevant to the WEC industry conducted in Section 2 was guided by the qualification process described in e.g. [SDWED, 2014]. Overall, the review evidenced two essential differences between WECs and other, more mature offshore applications:

1. Being (in general) unmanned structures, the safety factors of WECs associated with a specific failure could potentially be lower than the ones currently recommended in the standards, as the consequence of failure may be reduced when compared to equivalent failure in a manned structure.
2. WEC subsystems may be subject to different loads, which may require consideration of specific dominant failure modes. For example, design for near resonance can lead to fatigue becoming a governing failure mechanism, which in turn affects WEC reliability.

In Table 3.1, a matrix summarises the different subsystems that are covered by existing technical specifications, guidelines and standards devised for industries such as the maritime, oil and gas and offshore wind sectors, along with the main gaps that should be bridged to support the standardisation of the WEC industry. A colour code is used to prioritise the standardisation effort required:

● (blue)	● (yellow)	● (red)
Low priority No gaps or few gaps identified, requiring only minor updates to the relevant standard(s).	**Medium priority** Significant gap(s) identified, requiring some revision of the relevant standard(s).	**High priority** Major gap(s) identified, requiring a significant revision of the relevant standard(s), or a new standard.

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Table 3.1 Identified gaps in the existing standards: Priority levels for developments

Subsystem(s)	Topic(s) covered	Identified gap(s)	Priority level
Hydrodynamic	Structural design. Fatigue assessment. Reliability assessment. Manufacturing and testing.	The interaction with the PTO system is typically not considered. The safety factors may be too conservative.	🔴
Reaction	Design approaches. Manufacturing and testing. Design and construction.	The interaction with the PTO system is typically not considered. The safety factors may be too conservative.	🔴
PTO	All off-the-shelf components. Strength analysis. Design, construction, inspection, testing. Manufacturing and testing. Machinery safety.	The interaction with advanced control strategy may need to be further considered. The mechanical loading and maintenance regime may be outside of the standard specifications.	🟡
Instrumentation and control	Functional and electromagnetic compatibility. Operating conditions, electrical interfaces, performance requirements and data transmission protocols. Safety requirements. Design and integration.	Operational safety, requirements for control systems.	🟡
Electrical generation and power transmission	Design. Operation. Power quality. Grid code compliance.	Existing standards designed for manned offshore structures.	🟡
Interface	Protective coating. Sealings.	The mechanical loading may be outside of the standard specifications (e.g. for sealings). Subsea electrical connectors are not covered.	🔵
Other aspects	Health and safety. Marine operations (except decommissioning).	Decommissioning of gravity-based structures are not covered. Some standardisation of the EIA processes involved would be beneficial.	🟡

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3.2 Next Steps

The high-level gap analysis provided in Section 3.1 can be considered a starting point for further standardisation work, highlighting some of the key issues that should be addressed to facilitate the design and development of the emerging WEC industry.

Following the preliminary identification of relevant documents, and as the MegaRoller project progresses, new technical specifications, guidelines and standards, or the revisions of those listed in this report may be identified, potentially bridging some of the gaps highlighted in this report. As part of the project, a continuous monitoring of the ongoing standardisation effort will therefore be performed, assessing the relevance and applicability of the specifications and guidelines to the MegaRoller project and to the WEC industry. In particular, it is expected that the following documents are reviewed, when available:

- IEC/TS 62600-2 - Electricity producing wave energy converters - Design requirements for marine energy systems, expected in 2020.
- PD IEC/TS 62600-40 Ed.1 Marine energy - Wave, tidal and other water current converters. - Part 40: Acoustic characterization of marine energy converters, currently under development and pending approval.

In addition, it is anticipated that the dissemination activities conducted throughout the MegaRoller project will support significantly the development of standards (see also [D6.3, 2018]). In particular, it is expected that the MegaRoller project will contribute to informing the standard requirements, through dissemination of the key test data produced and associated analysis and findings. Such dissemination activities may be achieved via workshops with the stakeholders of the industry, or presentations at relevant conferences or relevant events (e.g. webinars, brokerage events, seminars).

Overall, the final key findings regarding the applicability of technical specifications, guidelines and standards to the MegaRoller technology and to the WEC industry will be documented at the completion of the project [D6.13, 2021], in an extension of present report, providing a view of the most up-to-date status of the standardisation work, along with clear recommendations for future activities.

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4 REFERENCES

[D6.13, 2021]	D6.13 *Standardisation report* Deliverable Leader: K2M Due date for submission 30/04/2021
[D6.3, 2018]	D6.3 *Dissemination plan* Deliverable Leader: SINTEF Dated 25/10/2018
[DNV GL, 2008]	Det Norske Veritas AS (DNV) DNV-OSS-312 Certification of Tidal and Wave Energy Converters October 2008
[DNV, 2005]	DNV Guidelines on Design and Operation of Wave Energy Converters May 2005 The Carbon Trust
[EMEC, 2009]	The European Marine Energy Centre (EMEC) Guidelines for Design Basis of Marine Energy Conversion Systems 2009
[GA, 2018]	Grant Agreement number: 763959 — MegaRoller — H2020-LCE-2016-2017/H2020-LCE-2017-RES-RIA-TwoStage Dated 26/03/2018
[IEC TS 62600-100:2012]	IEC TS 62600-100:2012 - Electricity producing wave energy converters - Power performance assessment
[IEC TS 62600-101:2015]	IEC TS 62600-101:2015 - Wave energy resource assessment and characterization
[IEC TS 62600-2]	IEC TS 62600-2 - Design requirements for marine energy systems
[SDWED, 2014]	Hameddni B., Bittencourt Ferreira C. (2014) *Deliverable D5.2 Generic WEC risk ranking and failure mode analysis* Dated 18/05/2014

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