MegaRoller

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763959

Project acronym:
MegaRoller

Project full title:
Developing the PTO of the first MW-level Oscillating Wave Surge Converter

Collaborative project

H2020-LCE-2017-RES-RIA-TwoStage

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D5.1 Validation methodology and plans

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Abstract
Goal Validation activities are an essential part of all product and system development processes. Validation of project results is also an important task in all research projects. In general in industrial context validation activities form a process to support the development process and to evaluate the results against the stakeholder requirements. Validation means confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. In MegaRoller project, a systematic validation process is developed to demonstrate that the models and technical solutions produced in the project meet the project objectives regarding Power Take Off (PTO) performance, power quality and reliability, and environmental and sosio-economic impact and cost reduction of the MegaRoller device. **Methods** The methodology developed in MegaRoller project combines systematic analysis, simulation and test methods. The aim is to ensure that the multi-technological and innovative MegaRoller device and its PTO system meets all the specified project objectives and system design requirements. The methodology covers activities for evaluation of PTO's functional performance, output power quality and reliability performance. It also covers life cycle costs and environmental and socio-economic aspects regarding the MegaRoller device and its operation and maintenance at its location. The evaluation criteria are derived and defined from the project objectives and adapted to the requirements issued by the EU for the demonstration of project results in Technology Readiness Level 5 (TRL5). **Results** This report describes the methodology developed and applied in MegaRoller project in the four above mentioned sections of the overall system evaluation. The methods and plans for PTO performance and power quality evaluation focus on the functionality of the PTO, power performance measurements (e.g. pressure, temperature, position and voltage measurements along the power conversion chain) and the power quality measurements (e.g. voltage and frequency of the electricity fed into the grid, and their variations). The methods and plans for the evaluation of reliability performance of the PTO system are based on Failure Mode, Effects and Criticality Analysis (FMECA) in a functional level. Reliability modelling and simulation approach utilizing Reliability Block Diagrams (RBD) is used to evaluate the achievable reliability performance levels for different PTO design options and component parameters. Assessment of environmental and socio-economic aspects is based on Environmental Impact Assessment (EIA) and Socioeconomic Impact Assessment (SEIA) models of the MegaRoller device. Life cycle Assessment (LCA) method is used to assess the cumulative environmental impacts of the MegaRoller device over space and time throughout its overall life cycle. The assessment of Life Cycle Costs (LCC) of the MegaRoller device aims at evaluating that the system design and the operating and maintenance concepts are able to achieve pursued cost reduction. The system cost breakdown structure is created and LCC of alternative designs are calculated using a LCC simulator tool.

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EXECUTIVE SUMMARY

Validation activities are an essential part of all product and system development processes. Validation of project results is also an important task in all research projects. The Horizon 2020 work programme 2018-2020 defines validation as one of the key elements of the Research and Innovation Action (RIA) projects. These projects may include basic and applied research, technology development and integration, testing and validation on a small-scale prototype in a laboratory or simulated environment. Projects may contain limited demonstration or pilot activities aiming to show technical feasibility in a near to operational environment.

In general in industrial context validation activities form a process to support the development process and to evaluate the results against the stakeholder requirements. Validation means confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. In MegaRoller research and innovation action a systematic validation process is developed to demonstrate that the models and technical solutions produced in the project meet the project objectives regarding PTO performance, power quality and reliability, and environmental and sosio-economic impact and cost reduction of the MegaRoller device.

The methodology developed in MegaRoller project combines systematic analysis, simulation and test methods. The aim is to ensure that the multi-technological and innovative MegaRoller device and its PTO system meets all the specified project objectives and system design requirements. The methodology covers activities for evaluation of PTO’s functional performance, output power quality and reliability performance. It also covers life cycle costs and environmental and socio-economic aspects regarding the MegaRoller device and its operation and maintenance at its location. The evaluation criteria are derived and defined from the project objectives and adapted to the requirements issued by the EU for the demonstration of project results in Technology Readiness Level 5 (TRL5). At TRL5 level the technologies should be validated in relevant environment i.e. industrially relevant environment in the case of key enabling technologies

This public report describes the methodology developed and applied in MegaRoller project in the four above mentioned sections of the overall system evaluation. The methods and plans for PTO performance and power quality evaluation focus on the functionality of the PTO, power performance measurements (pressure, temperature, position and voltage measurements along the power conversion chain) and the power quality measurements (voltage and frequency of the electricity fed into the grid). The methods and plans for the evaluation of reliability performance of the PTO system are based on Failure Mode, Effects and Criticality Analysis (FMECA) in a functional level. Reliability modelling and simulation approach utilizing reliability block diagrams (RBD) is used to evaluate the achievable reliability performance levels for different PTO design options and component parameters. Assessment of environmental and socio-economic aspects is based on Environmental Impact Assessment (EIA) and Socioeconomic Impact Assessment (SEIA) models of the MegaRoller device. Life cycle Assessment (LCA) method is used to assess the cumulative environmental impacts of the MegaRoller device over space and time throughout its overall life cycle. The assessment of life cycle costs (LCC) of the MegaRoller device aims at evaluating that the system design and the operating and maintenance concepts are able to achieve pursued cost reduction. The system cost breakdown structure is created and LCC of alternative designs are calculated using a LCC simulator tool.

The validation and impact assessment results will be presented in separate confidential reports.

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1 INTRODUCTION

Validation activities are an essential part of all product and system development processes. Validation of project results is also an important task in all research projects. The Horizon 2020 work programme 2018-2020 defines validation as one of the key elements of the 'Research and innovation actions' (RIA) projects. It is stated that these projects may include basic and applied research, technology development and integration, testing and validation on a small-scale prototype in a laboratory or simulated environment. Projects may contain limited demonstration or pilot activities aiming to show technical feasibility in a near to operational environment (EU HORIZON, 2017).

In general the term validation is defined from quality management perspective in ISO 9000:2015 'Quality management systems - Fundamentals and vocabulary' standard as follows:

> ***Validation*** *means confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. The objective evidence needed for a validation can be e.g. the result of a test* (ISO 9000:2015).

For comparison, it is also a good to read the definition of the term verification defined in ISO 9000:2015:

> ***Verification*** *means confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. The objective evidence needed for a verification can be e.g. the result of an inspection.*

1.1 Validation Process

In research projects validation activities are conducted as research tasks but from the general systems engineering perspective validation must be understood as a process, which is an essential part of the overall system development process. The ISO/IEC/IEEE 15288:2015 standard dealing with all the systems engineering processes describes the validation process as follows:

> *The purpose of the* ***validation process*** *is to provide objective evidence that the system, when in use, fulfils its business or mission objectives and stakeholder requirements, achieving its intended use in its intended operational environment.*

ISO/IEC/IEEE 15288:2015 also expresses that the objective of validating a system or system element is to acquire confidence in its ability to achieve its intended mission, or use, under specific operational conditions. This process should provide the necessary information so that identified anomalies can be resolved. In other words validation should confirm that the "right" system has been implemented or integrated to fulfil stakeholder requirements or expectations.

From the systems engineering point of view the set of stakeholder requirements and other requirements used for validation should be output from the stakeholder requirements definition process. The validation activities should be conducted either in the system's actual operational environment or in system's simulated operational environment. Validation can be done with simulation or mathematical modelling, with a technology prototype, with a pre-production prototype or with a delivered or installed system, as appropriate regarding the applicable system life cycle stage (ISO/IEC/IEEE 24748-2:2018).

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1.2 MegaRoller project

The MegaRoller project (https://www.sintef.no/MegaRoller), funded from the European Union's Horizon 2020 research and innovation programme, aims to generate extensive know-how in the area of Power Take Off (PTO) design and PTO control systems, with the ambitious goal to decrease the Levelized Cost of Energy (LCOE) of next generation Oscillating Wave Surge Converters (OWSC) devices below 150€/MWh.

The project will combine hardware improvements (designed to increase reliability, power density, power quality and decrease costs) with algorithm improvements (designed to improve power capture and power conversion efficiency, including in array scenarios). The methodologies used in the project (such as wave-by-wave damping control and prediction, standardized power units) will be applicable to many other Wave Energy Converter (WEC) types and generate new standards (algorithms) for PTO control. The project will combine for the first time machine learning technologies with auditory neuroscience in order to develop wave prediction algorithms based on Echo State Networks (ESNs) to be used in high performance wave damping control.

The project objectives have been structured into four areas and monitored by key performance indicators. The MegaRoller project aims to reduce the LCOE of the system below 150€/MWh, by increasing nominal device capacity (lower Capital Expenditure (CAPEX)/MW and Operating Expense (OPEX)/MW), reducing and standardizing the number of components (lower cost of components), increasing the PTO reliability (lower CAPEX, OPEX and higher availability) and reducing power conversion losses (higher power output).

The MegaRoller project will develop and demonstrate a PTO and PTO control systems for a 1MW OWSC device. The novel hardware solution features a modular design, twin drive trains, intelligent cylinders, standardized central power unit and novel accumulator arrangement while the innovative PTO control systems and algorithms feature wave-by-wave damping control, advanced efficiency control, energy storage control, power smoothing and prediction. The novel hardware will support a higher standardization of WECs through its modular design: standardized components developed in the project (such as accumulators and central power unit) will be available to WEC manufacturers.

The MegaRoller project will demonstrate and validate a full-scale PTO in a PTO test rig available at AW-Energy Oy in Finland. The test rig allows the consortium to create power matrices for the wave conditions of different sites, fine-tune the PTO control algorithms, certify the operation of the PTO and ensure that the produced electricity conforms to the various grid codes of different market areas.

1.3 Objectives and scope for the validation and impact evaluation

In MegaRoller project, a systematic validation process is developed to demonstrate that the models and technical solutions produced in the project meet the project objectives regarding PTO performance, power quality, environmental and sosio-economic impact, reliability and cost reduction.

The evaluation criteria are derived and defined from the project objectives and adapted to the requirements issued by the EU for the demonstration of project results in Technology Readiness Level 5 (TRL5). It is stated that in TRL 5 technology should be validated in relevant environment i.e. industrially relevant environment in the case of key enabling technologies (EU HORIZON, 2017).

The methodology developed in this case combines systematic analysis, simulation and test methods to ensure that the multi-technological and innovative PTO system meets all the specified objectives and

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design requirements. It will cover the following activities, targeting validation of performance testing, system reliability and life cycle costs and environmental and socio-economic aspects:

- **Validation of PTO performance and power quality**. These validation activities will focus on the functionality of the PTO, power performance measurements (pressure, temperature, position and voltage measurements along the power conversion chain) and the power quality measurements (voltage and frequency of the electricity fed into the grid).

- **Validation of reliability performance of the PTO system.** These validation activities will be based on a reliability analysis, e.g. Failure Mode, Effects and Criticality Analysis (FMECA) from a functional level down to a component level. A reliability performance model of the PTO will be created to evaluate the achievable reliability performance levels for different design options and parameters and to define the confidence in achieving the stated MegaRoller design targets.

- **Assessment of environmental and socio-economic aspects of the MegaRoller device**. The assessment will focus on the evaluation of the environmental and socio-economic impacts of the MegaRoller device.

- **Assessment of Life Cycle Costs (LCC) of the MegaRoller device.** The assessment of LCC of the new MegaRoller design will aim at evaluating that the new system is able to achieve pursued cost reduction. LCC of alternative designs will be evaluated to support the selection of cost-effective solutions.

1.4 Purpose and scope of this document

The purpose of this document is to define and introduce the validation methodology specified for MegaRoller project and to describe how the validation activities were conducted or will be conducted in the project.

This document describes methodology of the four main areas of PTO and MegaRoller device validation in the project:

- Validation of PTO performance and power quality by testing and measuring in the test bench;
- Validation of PTO system reliability performance by analysis, modelling and simulations;
- Assessment of life cycle costs of the MegaRoller device by defining cost elements, modelling the cost break-down structure and calculations;
- Assessment of environmental and socio-economic aspects of the MegaRoller device by defining impact factors, modelling and evaluating.

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2 VALIDATION OF PTO PERFORMANCE AND POWER QUALITY

The MegaRoller PTO system will be operated in the upgraded test bench. The tests will be started with basic functional tests. The focus of the test is on the functionality of the PTO, power performance measurements and the power quality measurements. The test bench will be operated with representative sea states and systematically the wave periods, heights, and directions will be gone through. Functional information, performance data and power quality data are collected simultaneously in all tests. The measurement results will be compared to the validation criteria and a validation table with clear marking of pass/no pass will be created. The results of these measurements provide feedback if the design requires changes after the MegaRoller project.

2.1 Test bench for the MegaRoller PTO

There are two individual electro-hydraulic machines, or systems, in the MegaRoller testing facility: the MegaRoller test bench and the MegaRoller PTO. The test bench is a machine that creates, or imitates, mechanical movements of the MegaRoller primary mover, the panel. The movement is generated with four large hydraulic pump units that are driving a large hydraulic cylinder that is moving back and forth according to the selected wave data. The MegaRoller PTO is the machine that is tested and validated in the MegaRoller project using the test bench. The systems are illustrated in Figure 2.1.

The MegaRoller power take-off system (PTO) and the MegaRoller testing bench systems are based on the WaveRoller wave energy converter (WEC) power take-off system and test bench developed and operated by AW-Energy Oy during years 2014-2018.

The test bench and the PTO are controlled with their own automation systems and their only interconnection is a mechanical connection between hydraulic cylinders. Basically, the test bench can be used without the PTO, or vice versa. The systems are connected to the same electricity supply which means that during testing, we only take the amount of electric energy from the grid that is equal to the losses generated in the systems.

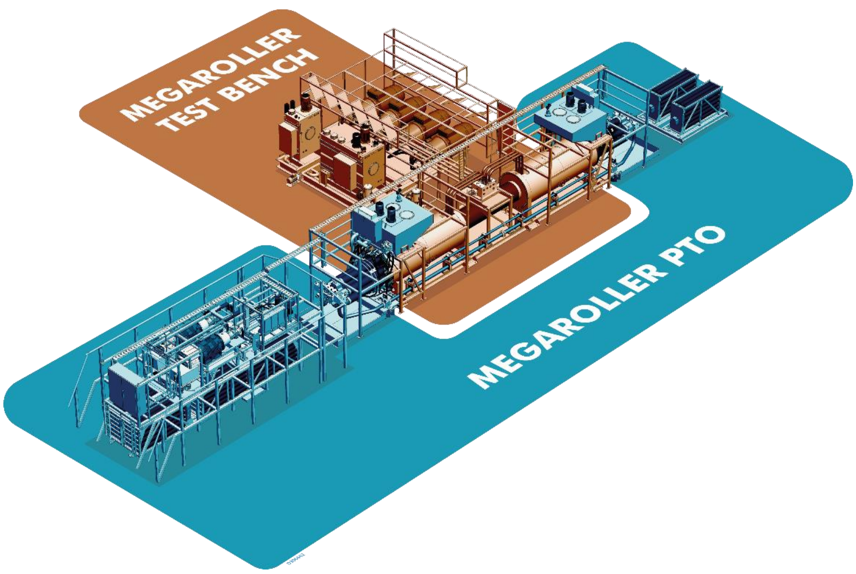

Figure 2.1 Layout of the MegaRoller testing facility.

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2.1.1 MegaRoller Test Bench

The main components of the test bench are four 500kW closed loop hydraulic pump units, and the main hydraulic cylinder, also known as the wave generator. The hydraulic pump units are controlled with frequency converters. The operation principle of the test bench is simple: the pump units are pumping oil into the main cylinder based on the wave data that is downloaded into the automation system. The more the pumps are pumping oil, the faster the cylinder moves. The movement direction of the wave generator is changed by changing the direction of the pumping.

The test bench is able to generate all sea states and waves required to test the performance of the MegaRoller PTO. Only the largest abnormal sea states or very large single waves cannot be reproduced which means that the full-scale survival of system in the largest waves cannot be tested in testing bench conditions. However, performance in those is not relevant if considering the performance of the PTO since the over 95% of the sea states in the world can be reproduced. Survival of the PTO is validated with calculations, and later with real life test in the ocean.

The maximum wave the test bench is able to generate is defined by the pumping capacity (=cylinder speed) and the grid connection power (=cylinder force). The testing facility has its own 2MW high voltage connection to the grid. Theoretically it is possible to use any kind of sea state data in the test bench, but before the wave generator can start moving, the automation system checks the selected sea state data and downsizes all waves that cannot be driven. The consistency between different test runs is compromised, if the data includes movements that cannot be reproduced.

The test bench can also be driven with different type sine waves that are extremely useful when testing PTO performance, for example performance of the cooling system or the generators. With sine waves, keeping certain power levels stable for longer periods is possible.

2.1.2 MegaRoller PTO

The PTO unit is a machine that resists and controls the movement of the panel according to the prevalent sea state and panel axle speed. When it is resisting rotation of the main axle of the panel with hydraulic cylinders, it is also capturing energy into the accumulators in the hydraulic system. Energy that is captured into the hydraulic circuit is transformed into electric power using hydraulic motors and electric generators. This electrical power is then fed into the subsea cable and via onshore substation to the grid. In the underwater device, all these elements of the PTO machine are enclosed inside a watertight structure and are not exposed to the marine environment.

In the test bench, energy is captured from the wave generator cylinder that is replacing the mechanisms of the panel. The PTO is connected to the test bench with a similar simple mechanical connection that is used in the underwater PTO in the future. Therefore, the electro-hydraulic performance of the PTO can be tested thoroughly in test bench conditions.

The PTO unit is a closed loop, two pressure level common rail system with multiple energy producing units (cylinders) and multiple energy consuming units (hydraulic motors). Due to the nature of ocean waves, hydraulic accumulators are also required for supporting power stability.

Basically, the common rail system has units that are either generating, storing, or consuming hydraulic energy. In the test bench conditions, hydraulic energy is generated with hydraulic cylinders by resisting the mechanical movement of the wave generator. This energy is stored temporarily inside hydraulic

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accumulator racks. Energy stored into the accumulator racks is consumed with hydraulic motor units that are connected to the same axle with electrical generators.

Electricity production of the PTO generators is controlled with frequency converters. One of the main purposes of the test bench is to validate that the energy exported to the grid fulfils the defined quality requirements, and the PTO is able to control the electricity generation process according to the grid status.

Because the actual PTO is assembled inside a hull and installed to the bottom of the sea, the PTO must always have two or more elements that are generating, storing, consuming energy. This way the PTO has higher tolerance against faults that would otherwise stop the energy production process completely. The common rail enables that there are multiple different entities inside the PTO, and they can used safely and redundantly. Redundant and partial operation of the PTO is also validated.

2.2 Operational tests

The functionalities of the PTO will be tested in the test bench. Tests will cover all operational aspects and they will proceed from simple test runs to the tests of more complicated functionalities. Firstly, it is verified that all electric and hydraulic actuators and sensors in the PTO system are operating correctly.

All operating modes and transitions between them will be tested. The most relevant operating modes of the PTO automation system are:

- Shutdown
- Ready
- Idling
- Running

In the shutdown mode, all controls are disabled, no pumps or motors are running and the common rail system is depressurized. It is verified that the system is in failure-safe state.

If the system is reset by an operator, the system moves to the ready mode. In this mode the PTO prepares itself for system start-up. For example, some water and oil pumping systems are activated, and it is possible to manually test different actuators if needed.

The system remains in the ready mode until the idling command is given. Transition from ready to idling mode includes different phases, for example pressurizing the common rail system, and connecting the hydraulic cylinders to the wave generator. When the system is in idling mode, the cylinders are moving together with the wave generator cylinder, oil flows in the common rails, and the PTO is ready for producing energy. It is verified that the system can be used safely in idling mode before the system can capture mechanical energy and transform it into electric energy. All sensors, actuators, pumps, and generator can be tested thoroughly in the idling mode.

When the run command is given, the system moves to the running mode. In this mode, the common rail system will have different pressure levels, called the high-pressure line and the low-pressure line. Basically, the cylinders are then taking oil from the low-pressure line and pressurizing it to the high-pressure line. On the other hand, the hydraulic motors are taking oil from the high-pressure line and returning it to the low-pressure line. The most important operational tests in the running mode are system operation in different type failure situations.

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The tests start with small sine waves before using realistic sea states or bigger sine waves. Basically, the wave generator is moving continuously during the tests because otherwise the behaviour of the PTO is not validated properly in all transitions.

The PTO can pass the operational tests only, if it can be used safely, and it operates according to requirements. If risks or hazards are detected, they are identified, documented and removed immediately.

2.3 PTO performance measurements

The function of the PTO unit is to capture the energy and to convert it into electric power. Therefore, the key performance criteria of the PTO are efficiency of the conversion process, and the stability and quality of output power. Reliability of the process is also one of the key performance criteria, but it cannot be tested in the test bench conditions. In the MegaRoller project, reliability is evaluated with FMECA method and RAM (Reliability, Availability and Maintainability) modelling and simulation method as explained in this report in chapter **Error! Reference source not found.**. PTO power quality measurements are covered in more details in the following chapter **Error! Reference source not found.**.

Efficiency of the PTO is determined along the power conversion chain. This will give efficiency for each step in the power conversion process. It is extremely important to know where power losses are generated so they can be effectively removed from the hydraulic system. Knowing the partial efficiencies of the system also enables that further development actions are directed correctly.

In most cases, efficiency (or power losses) of a component is determined by measuring pressure losses caused by the component, for example a valve or a pipe. Since the purpose is to maximize efficiency, all pressure losses are negative impacts. Losses are always measured as a function of the cylinder speed. It should be noted that the system cannot be designed to operate with high efficiency over the whole speed range. Therefore, it is important to verify that power losses are low with the most prevalent sea states. Pressure losses are measured with sensors that are more accurate than normal pressure sensors used in the automation system.

Measuring pressure difference is the primary method to determine efficiency of a simple hydraulic component but some assemblies require more sophisticated measurements. For example, efficiency of a hydraulic motor is dependent on the pressure difference between the common rails, adjusted motor volume, and rotation speed of its axle. Therefore, instead of measuring just the efficiency of the hydraulic motor, it is easier to measure the efficiency of the whole power conversion system including the hydraulic motor, an electric generator, and a frequency converter. Basically, we are measuring how efficiently hydraulic pressure and oil flow are converted into electric power at grid frequency. Purpose of this measurement is to generate a chart where power conversion efficiency is visualized as a function of hydraulic motor volume, common rail pressure, and axle speed. We will also measure how effectively mechanical force and speed are converted into hydraulic pressure and oil flow. This requires very accurate cylinder speed measurements, and high accuracy pressure sensors.

All the different key performance indicators cannot be optimized at the same time. Basically, if power stability and quality need to be maximized, we always lose some power and have lower efficiency since stability of oil flow and pressure in the common rails need to be maximized also. And if efficiency of the system and energy capture are maximized, stability of output will be lower. The main goal of the commissioning and pretesting phase of the PTO is to adjust the control software parameters so that all the performance indicators are balanced and are in line with power quality requirements.

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PTO performance results will be reported in deliverable D5.4 'PTO performance and power quality validation results. The report visualizes performed performance tests, their results and if the acceptance criteria of each test were met.

2.4 PTO power quality measurements

PTO power quality will be measured according to the valid and relevant standards using voltage and frequency measurements of the electricity fed into the grid. The technical specification **IEC TS 62600-30:2018** 'Marine energy - Wave, tidal and other water current converters - Part 30: Electrical power quality requirements' describes definitions and specifications of the quantities to be determined for characterizing the power quality of marine energy (wave, tidal and other water current) converter units. It also presents measurement procedures for quantifying the characteristics of a marine energy (wave, tidal and other water current) converter. The measurement procedures are valid for a single marine energy converter (MEC) unit (or farm) with three-phase grid or an off-grid connection. The measurement procedures are valid for any size of MEC unit.

An overview of the relevant international standards developed for power quality measurements any supply terminal in public European electricity networks is presented in Figure 2-2.

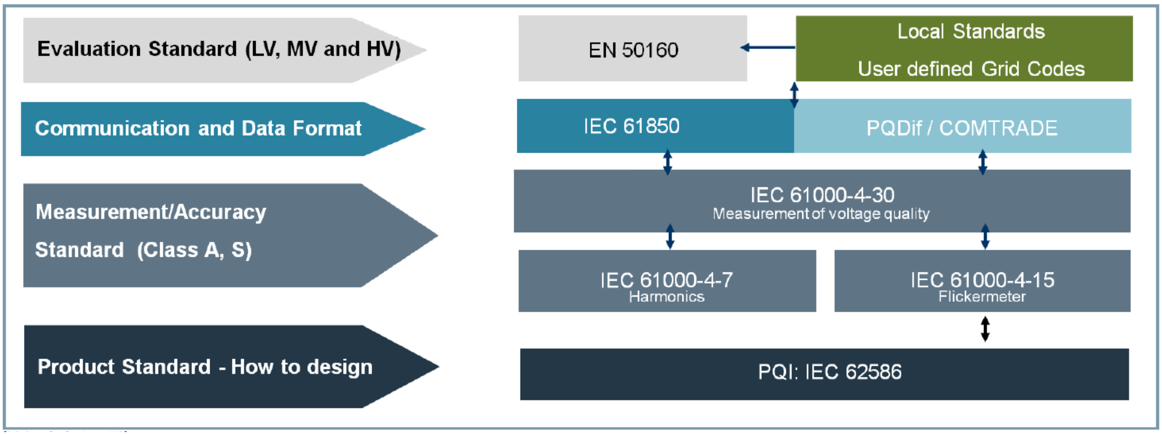

Figure 2-2 An overview of the power quality standards (Siemens 2021)

2.4.1 Reference standards for power quality measurements

The PTO power quality measurements will be designed according following standards:

EN 50160:2010 +A1:2015 + A2:2019 + A3:2019 'Voltage characteristics of electricity supplied by public distribution systems'. This European Standard describes the limits or values within which the voltage characteristics can be expected to remain at any supply terminal in public European electricity networks and does not describe the average situation usually experienced by an individual network user.

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The standard defines, describes and specifies the main characteristics of the voltage at a network user's supply terminals in public low voltage, medium and high voltage AC electricity networks under normal operating conditions.

- low voltage: voltage whose nominal r.m.s. value is Un ≤ 1 kV
- medium voltage: voltage whose nominal r.m.s. value is 1 kV < Un ≤ 36 kV
- high voltage: voltage whose nominal r.m.s. value is 36 kV < *U*n ≤ 150 kV

'r.m.s value' is an abbreviation of 'Root mean square value'.

The voltage characteristics given in this standard are not intended to be used as electromagnetic compatibility (EMC) levels or user emission limits for conducted disturbances in public electricity networks. The voltage characteristics given in this standard are not intended to be used to specify requirements in equipment product standards and in installation standards. This standard may be superseded in total or in part by the terms of a contract between the individual network user and the network operator. Measurement methods to be applied in this standard are described in EN 61000-4-30.

IEC 61000-4-30:2015+AMD1:2021 CSV (Consolidated version) 'Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods'. IEC 61000-4-30:2015+AMD1:2021 CSV defines the methods for measurement and interpretation of results for power quality parameters in AC (alternating current) power supply systems with a declared fundamental frequency of 50 Hz or 60 Hz. Measurement methods are described for each relevant parameter in terms that give reliable and repeatable results, regardless of the method's implementation.

The standard addresses measurement methods for in-situ (i.e. "on site", "in position" or "locally") measurements. Measurement of parameters covered by this standard is limited to conducted phenomena in power systems. The power quality parameters considered in this standard are:

- power frequency,
- magnitude of the supply voltage,
- flicker,
- supply voltage dips and swells,
- voltage interruptions,
- transient voltages,
- supply voltage unbalance,
- voltage harmonics and inter-harmonics,
- mains signalling on the supply voltage,
- rapid voltage changes, and
- current measurements.

Emissions in the 2 kHz to 150 kHz range are considered in Annex C of the standard (informative), and over- and under-deviations are considered in Annex D (informative). Depending on the purpose of the measurement, all or a subset of the phenomena on the above mentioned list may be measured.

The IEC 61000-4-30:2015 standard defines the measurement method, accuracy and time aggregation to verity of power quality parameters in 3 performance classes to obtain repeatable and comparable results. The IEC 61000-4-30:2015 defines three performance classes as follow (Elspec, 2021):

- **Class A – must to comply to the highest performances and accuracy level to obtain repeatable and comparable results**

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- Class S – accuracy levels are less stringent. Class S Power quality analysers can be used for statistical surveys and contractual application where comparable measurement are not required.
- *Class B (obsolete) – This class was introduced at the 1st and 2nd editions of the standard to avoid making may instrument obsolete. In this class the standard required that the measurement method and accuracy will be defined by the manufacturer in the instrument datasheet. In the 3rd addition, this performance class was removed.*

Additionally, IEC 62586-1:2017 defines EMC, safety and environmental requirement for power quality analysers in different installation conditions and IEC 62586-2:2017 defines the test and uncertainty requirement to comply with IEC 61000-4-30 class A.

IEC 61000-4-7:2002+AMD1:2008 CSV (Consolidated version) 'Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and inter-harmonics measurements and instrumentation, for power supply systems and equipment connected thereto'. IEC 61000-4-7:2002+A1:2008 CSV applies to instrumentation intended for measuring spectral components in the frequency range up to 9 kHz which are superimposed on the fundamental of the power supply systems at 50 Hz and 60 Hz.

For practical considerations, this standard distinguishes between harmonics, inter-harmonics and other components above the harmonic frequency range, up to 9 kHz. It defines the measurement instrumentation intended for testing individual items of equipment in accordance with emission limits given in certain standards (for example, harmonic current limits as given in IEC 61000-3-2:2018 +AMD1:2020 CSV 'Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current ≤16 A per phase)) as well as for the measurement of harmonic currents and voltages in actual supply systems.

IEC 61000-4-15:2010 RLV (Redline version) 'Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flicker meter - Functional and design specifications'. IEC 61000-4-15:2010 gives a functional and design specification for flicker measuring apparatus intended to indicate the correct flicker perception level for all practical voltage fluctuation waveforms.

The standard gives a method for the evaluation of flicker severity on the basis of the output of flicker meters complying with this standard. The flicker meter specifications in this part of IEC 61000 relate only to measurements of 120 V and 230 V, 50 Hz and 60 Hz inputs. Detailed specifications for voltages and frequencies other than those given above, remain under consideration. The object of this part of IEC 61000 is to provide basic information for the design and the instrumentation of an analogue or digital flicker measuring apparatus. It does not give tolerance limit values of flicker severity. This new edition of the standard adds or clarifies the definition of several directly measured parameters, so that diverging interpretations can be avoided. The standard has the status of a basic EMC publication in accordance with IEC Guide 107.

IEC 62586-1:2017 'Power quality measurement in power supply systems - Part 1: Power quality instruments (PQI)' IEC 62586-1:2017 defines the minimum set of parameters that must be implemented for Power Quality Instruments. IEC 62586-1:2017 specifies product and performance requirements for instruments whose functions include measuring, recording and possibly monitoring power quality parameters in power supply systems, and whose measuring methods (class A or class S) are defined in IEC 61000-4-30:2015.

These requirements are applicable in single, dual- (split phase) and 3-phase AC power supply systems at 50 Hz or 60 Hz. The standard has the status of a basic EMC publication in accordance with IEC Guide 107.

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IEC 62586-2:2017 'Power quality measurement in power supply systems - Part 2: Functional tests and uncertainty requirements'. IEC 62586-2:2017 specifies functional tests and uncertainty requirements for instruments whose functions include measuring, recording, and possibly monitoring power quality parameters in power supply systems, and whose measuring methods (class A or class S) are defined in IEC 61000-4-30:2015. The standard applies to power quality instruments complying with IEC 62586-1.
The standard can also be referred to by other product standards (e.g. digital fault recorders, revenue meters, MV or HV protection relays) specifying devices embedding class A or class S power quality functions according to IEC 61000-4-30. The requirements in the standard are applicable in single-, dual- (split phase) and 3-phase AC power supply systems at 50 Hz or 60 Hz.

2.4.2 Measurement parameters for power quality measurements

The class A measurement parameters according to IEC 61000-4-30:2015+AMD1:2021 CSV are described in the following subsections 2.5.2.1 - 2.5.2.8. PTO power quality parameters are calculated from measured line currents and voltages using false neutral by connecting voltage low terminals together enabling to indicate power and voltage in each phase (Figure 2-3).

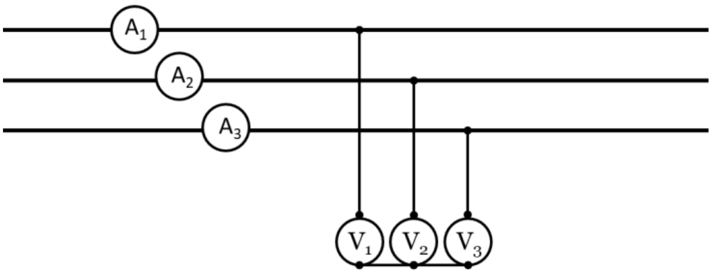

Figure 2-3 A simplified presentation of the 'Three wattmeter' method.

2.4.2.1 Time aggregation intervals

The IEC 61000-4-30:2015 class A defines four aggregation intervals (Figure 2-4):

- 10/12 cycles (~200ms) at 50/60Hz respectively. The interval time varies with actual frequency.
- 150/180cycles (~3sec) at 50/60Hz respectively. The interval time varies with actual frequency.
- 10min interval begins on an absolute 10min time
- hours interval begins on an absolute even 2h time

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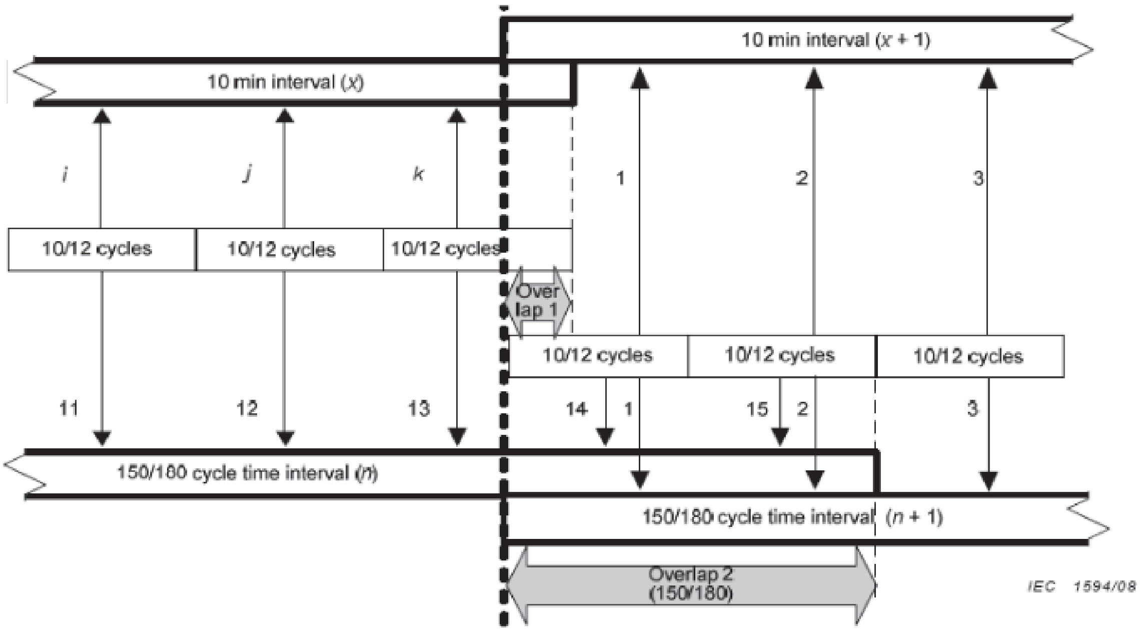

Figure 2-4 The time aggregation scheme (IEC 61000-4-30:2015)

2.4.2.2 Power frequency

Number of cycles are measured during 10 seconds time intervals. The frequency is calculated by dividing the number of total cycles by the duration of the total number of cycles. Range for 50Hz system is from 42.5Hz to 57.5Hz and for 60Hz system 51Hz to 69Hz with uncertainty of 0,01Hz. (Legarreta et. al, 2011)

2.4.2.3 Magnitude of the supply voltage and current

Magnitudes of the voltage and current are the (root-mean-square) RMS value obtained over four time aggregation intervals listed in chapter 2.5.2.1. (IEC 61000-4-30:2015)

2.4.2.4 Flicker, Supply voltage dips, swells and Rapid Voltage Change

IEC 61000-4-15 defines intensity of flicker annoyance parameters long term severity (P_{lt}) and short term severity (P_{st}). P_{st} is measured over 10 minute period and P_{lt} over two hour period from 12 P_{st} values. Figure 2-5 depicts five functional blocks of the standard:

- First block works as an signal condition unit
- Square multiplier block together with high pass filter of the third block works as a demodulator.
- Third blocks first filter eliminates the DC component and it should first order filter. Next low pass filter should be 6th order Butterworth. Weighing filter simulates the nature of human visual system
- 4th block performs squaring and smoothing operation that simulates brain visual and tries to emulate brain's memory with 1st –order filter with 300ms time constant. Output is instantaneous flicker P_{inst} .
- In 5th block statistical analysis is done with percentile evaluation using equations 1 and 2 (Kolek et al. 2021).

$$P_A = 0.314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s} \qquad 1)$$
$$P_{st} = \sqrt{P_A}$$

Where:

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$$
\begin{aligned}
P_{50s} &= (P_{30} + P_{50} + P_{80})/3 \\
P_{10s} &= (P_6 + P_8 + P_{10} + P_{13} + P_{17})/5 \\
P_{5s} &= (P_{2.2} + P_3 + P_4)/3 \\
P_{1s} &= (P_{0.7} + P_1 + P_{1.5})/3
\end{aligned} \quad (2)
$$

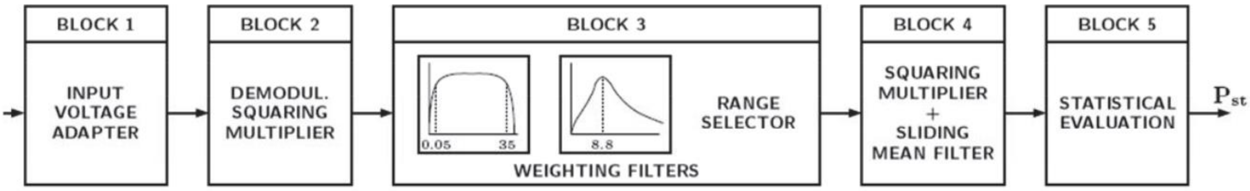

Figure 2-5 A functional block diagram of a flicker meter (following IEC 61000-4-15:2010 standard) (Legarreta et al. 2011]

When supply voltage dip occurs the voltage r.m.s. value drops 10% from specified level for a short period of time. The voltage swell is the opposite to the voltage dip and voltage r.m.s. increases over 10% from specified level for a period of ½ cycle to 1minute (Figure 2-6).

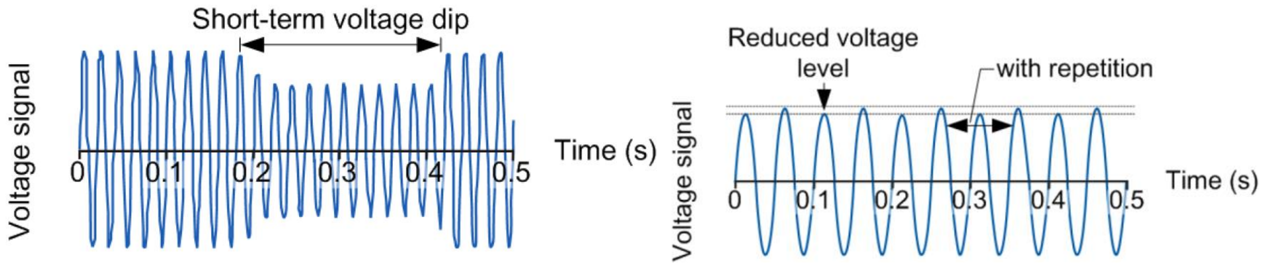

Figure 2-6 Short-term voltage dip and RVC (Siemens 2017)

2.4.2.5 Voltage interruptions and transient voltages

Interruption is power outage short or long period can be caused by lightning strike or circuit breaker tripping. Transient overvoltage impulses can occur from the same reasons (Figure 2-7).

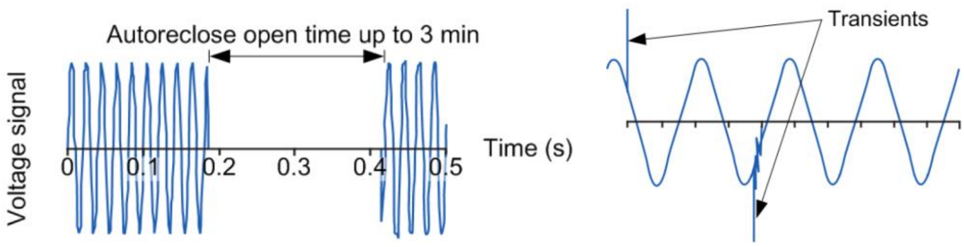

Figure 2-7 An example of voltage interrupt and transients (Siemens 2017)

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2.4.2.6 Voltage and current harmonics and inter harmonics

Harmonics are calculated in 10/12 cycle aggregation intervals to 5Hz FFT (Fast Fourier Transform) bins (also called as frequency points) from which harmonic and inter-harmonic subsets are calculated. The Total Harmonic Distortion (THD) factor is the ratio of the sum of the r.m.s. of the harmonic amplitudes to the r.m.s. value of the fundamental amplitude (See the equation 3).

$$THD = \sqrt{\sum_{n=2}^{H} \left(\frac{G_n}{G_1}\right)^2} \quad (3)$$

Where G_n is the value of harmonic component and G_1 is the fundamental component

2.4.2.7 Mains signalling voltage on the supply voltage

Mains signalling voltage is the mean voltage over 150/180 cycle aggregation time.

2.4.2.8 Unbalance, under-deviation and over-deviation

Voltage unbalance is calculated from symmetrical components from voltage fundamentals 10/12 cycle values. Calculated symmetrical components V_Z, V_P, V_N .are the r.m.s. values of zero, positive and negative system. Unbalance is calculated using following formulas [$V_2 = (V_N / V_P)*100\%$, $V_0 = (V_Z / V_P)*100\%$]. Under- and over-deviation indicates if the signal in given aggregation was higher or lower than nominal voltage (Fluke 2017).

$$V_Z = \frac{1}{3}\sqrt{(V_1 + V_2 * \cos\varphi_{12} + V_3 * \cos\varphi_{13})^2 + (V_2 * \sin\varphi_{12} + V_3 * \sin\varphi_{13})^2}$$

$$V_P = \frac{1}{3}\sqrt{V_1 + V_2 * \cos(\varphi_{12} + 120^\circ) + V_3 * \cos(\varphi_{13} + 240^\circ)^2 + V_2 * \sin(\varphi_{12} + 120^\circ) + V_3 * \sin(\varphi_{13} + 240^\circ)^2} \quad (5)$$

$$V_N = \frac{1}{3}\sqrt{V_1 + V_2 * \cos(\varphi_{12} + 240^\circ) + V_2 * \cos(\varphi_{13} + 120^\circ)^2 + V_2 * \sin(\varphi_{12} + 240^\circ) + V_3 * \sin(\varphi_{13} + 120^\circ)^2}$$

V_Z, V_P, V_N	rms values of zero, positive, and negative system
V_1, V_2, V_3	rms values of the fundamentals of the phase voltages
φ_{12}, φ_{13}	phase angles between phases 1 and 2, phases 1 and 3 (nominal: -120° and -240°)

Under-deviation: $U_{under} = 0$, if $U_{RMS} > U_{nom}$, else $U_{under} = (U_{nom} - U_{RMS} / U_{nom})*100\%$

Over-deviation: $U_{over} = 0$, if $U_{RMS} < U_{nom}$, else $U_{over} = (U_{RMS} - U_{nom} / U_{nom})*100\%$

2.4.3 Reporting the power quality measurement results

PTO performance and power quality validation results will be reported in deliverable D5.4 ‘PTO performance and power quality validation results’. The report will lists tests performed, test results and clear indication if the objectives and acceptance criteria of each test were met.

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3 VALIDATION OF RELIABILITY PERFORMANCE OF THE PTO SYSTEM

To achieve profitable electricity production, system dependability and especially reliability as one of its elements are key issues to be considered in the MegaRoller system design. To be able to provide a comprehensive evaluation of system reliability performance, a number of system analyses are performed. The reliability-centred development approach applied in this project consists of readily existing analysis methods: Failure Mode, Effects and Criticality Analysis (FMECA) and reliability modelling and simulation using Reliability Block Diagrams (RBDs). Additionally, as reliability performance and its improvement are highly interconnected with the life cycle costs of the system, the connections to Life Cycle Cost (LCC) analysis also needs to be considered. Thus, none of these analyses are considered here as stand-alone efforts, but instead they are used in combination to provide support for the system design and to estimate system reliability and profitability.

3.1 Research on reliability aspects of WECs

Reliability of WECs has been studied already in the 1970s and 80s (Wolfram, 2006), but most advances in WEC technologies have emerged only during the past decade. Due to the nature of wave energy as a relatively new field of study in engineering, there is only a limited number of research references available regarding the reliability aspects of WEC devices. A major part of the available research focuses on fatigue-related phenomena on the mechanical structures, caused by the varying loads imposed by different sea states (Ambühl et al., 2015; Ransley, 2015), as well as survivability of the WEC device in the extreme maritime conditions, such as during storms (Coe & Neary, 2014).

So far, significantly smaller focus seems to have been placed on the Power Take-Off (PTO) systems of WECs, with very limited references available (Henderson, 2006). While the PTO can mostly consist of well-known components, the unusual operating conditions are likely to affect the reliability performance of these established components as well (Wolfram, 2006). In addition, as typical for most new technologies, available studies mostly focus on technical aspects of reliability. However, some studies have also been published towards understanding the economic implications of WEC system reliability and, for example, the related maintenance strategies (McAuliffe et al., 2015; Heikkilä et al., 2019).

It should also be noted that different WEC devices operate with a very wide range of operational principles, and may have drastically different reliability characteristics depending on the design goals, operating conditions, and reliability performance requirements set to the device. Because of the large number of different WEC types, most available studies focus on specific WEC systems, mostly with rather different characteristics from the OWSC type design of the MegaRoller concept introduced in this paper. For example, Ambühl (2015) has extensively reviewed two types of WECs, both of which are floating devices (in contrast to the submerged MegaRoller). Similarly, Cretu et al. (2016), Mueller et al. (2016) and Thies (2012) have all studied different types of WECs. These studies apply varying methods for failure identification (including e.g. FMEA) and probabilistic methods, such as Reliability Block Diagrams (RBD) and Bayesian statistics for reliability prediction.

As a common finding in these studies, it is apparent that a high level of uncertainty is characteristic for reliability assessments of WECs due to the lack of reliability data from previous installations and due to the wide range of new WEC technologies and installation sites. Previous research also suggests that because of the uncertainties related to WEC reliability data, information from other domains with similar characteristics should be incorporated whenever relevant. This is because other offshore domains, such as wind energy or oil and gas sector, share some characteristics related to reliability requirements and environmental conditions with WECs. They also have a longer tradition with some publicly available

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reliability related data. Research in these fields can support reliability prediction, but also more comprehensive techno-economic studies (Tiusanen et al. 2020).

3.2 Limited possibilities for maintenance sets up the reliability targets

Wave Energy Converters (WEC) that are installed in the sea bottom, require high reliability to fulfil the energy production and Levelized Cost of Energy (LCOE) targets. As the system is submerged under water for operation, the possibilities to conduct traditional preventive and corrective maintenance actions are very limited. In practice, during the operation, only superficial maintenance operations are possible, such as surface cleaning from biofouling and visual inspections. For this reason, the importance of operational reliability must be emphasized from the very beginning of the WEC design.

The reliability targets for WEC design have to be set according to the energy production goals and the location of production site. The estimated energy production can be calculated by taking into account both the system design properties and the conditions of operational environment where the WEC will be installed. These estimations play an important role when defining the timeframe that is available for major overhaul and maintenance actions and the limits and range for the allowed component efficiency decrease during the period between the major maintenance actions.

As the possibilities to conduct preventive maintenance are very limited, they also set the reliability targets for most of the components. The goal is to get the operational reliability to the level where mean time between major overhaul, i.e. bringing the WEC on surface for planned maintenance can be achieved. During the major overhaul, the WEC is checked thoroughly and all the wearables like sealings, will be replaced.

3.3 System approach to reliability engineering

In machinery design, reliability engineering is typically started from analysing component failures according to the system breakdown structure that describes the component level design. This means that in this point the whole machinery system is already designed to detail level although it is well known that the most appropriate way to affect the system reliability characteristics is to focus on the beginning of the system development in conceptual design phase.

The system approach to reliability engineering in this context means the mind-sets and procedures to guide the reliability engineering work to right system hierarchy level and to enable the use of available but partly uncertain information for system modelling, system analyses and simulations.

In general, the systems-engineering principles are said to be scalable plans of actions including company-specific applications of life cycle and systems-engineering processes, decisions on system architecture, and requirement specifications and management. In this context, systems engineering efforts can be utilised for the development of the entire wave energy park as well as a single WEC.

The main characteristics of systems engineering can be summarised by listing them as systematic and extensive requirement specifications and management, systematic verification of design solutions and validation of implementations, and breaking down of system design problems into manageable sub-problems (Granholm, 2013).

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Reliability engineering should be understood as one of the systems analysis and control efforts in the iterative systems engineering process. It emphasizes dependability aspects in the lifecycle management of a product (Figure 3-1). The general purpose of systems-analysis efforts is to resolve conflicts identified in systems-engineering tasks, to manage risks throughout the systems engineering efforts, and to support the overall process to end up with balanced requirements and design solutions (ISO IEC 26702:2007).

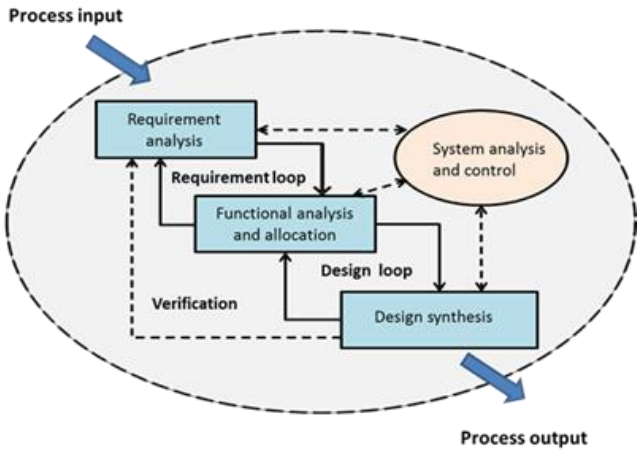

Figure 3-1 A simplified flowchart of the systems-engineering process (DoD DAU, 2001).

Based on our experience in other fields of industry we have a strong view that systematic reliability engineering methods can offer valuable support for the design and evaluation of highly automated multi-technical WEC systems. The system approach we are studying and developing for reliability engineering is based on the Top-Down approach (INCOSE, 2015) starting from the evaluation of alternative conceptual designs. The reliability engineering work should then continue supporting the system design in various system development phases. Although the information in early conceptual design phases is inadequate and includes uncertainties, it is important to bring up system reliability related aspects, assess risks and allocate system reliability requirements.

The reliability engineering methodology in this system approach consists of well-known methods that are commonly used to support industrial product design to ensure that customer expectations for reliability are met throughout the life of the product with low overall life-cycle costs. The methods studied and applied in the MegaRoller project are:

- Potential Problem Analysis (PPA) for the identification of system availability risks of a wave energy park and a single OWSC (e.g. a MegaRoller device).
- Functional modelling of the PTO using Functional Block Diagrams (FBD)
- Failure Mode, Effects and Criticality Analysis (FMECA) of the PTO,
- Reliability modelling using Reliability Block Diagrams (RBDs) and simulation of selected subsystems of the PTO,
- Life Cycle Cost (LCC) modelling and calculations of the MegaRoller device

3.4 Potential problem analysis (PPA)

PPA is an early stage risk analysis method that can be used to reveal potential reliability problems in systems that are in concept phase (Reunanen, 1993). The main phases of PPA are presented in Figure 3-2.

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PPA is a group-working method which is based on silent brainstorming principle. In the first phase the basic information of the design or operating concept is presented for the participants and they are asked to write down their concerns on the concept's functionality or other related issues affecting the system performance. This is called silent brainstorming. The written concerns can be circulated during the session among the participants and this way give some new ideas for the further brainstorming of problems. In the first phase there can be a lot of people involved.

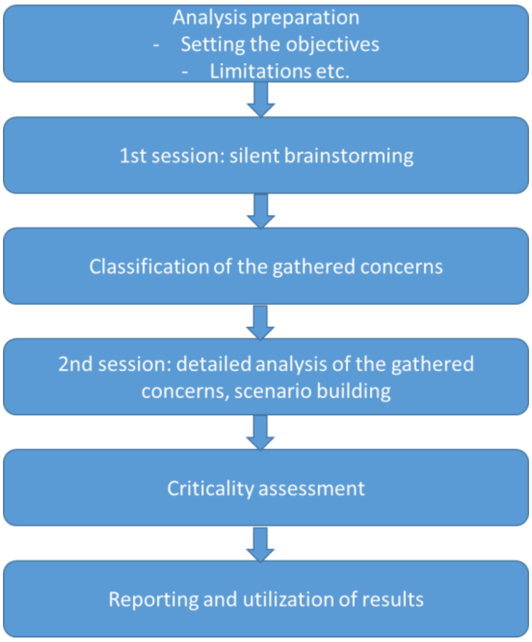

Figure 3-2 Main phases of the PPA process.

In the second phase the concerns gathered with silent brainstorming will be analysed in more detail by a smaller group of experts. The findings of the first phase are classified into some categories depending on the situation - sometimes the concerns can be classified according to e.g. project phases, system lifecycle, technical division etc. whichever is considered appropriate. The causes and consequences will be identified for all concerns and according to the scenario, also corrective actions can be identified. Also risk ranking can be accomplished, if required.

3.5 Functional modelling of the MegaRoller PTO system

The basis for reliability validation of the PTO system is formed by Failure Mode, Effects and Criticality Analysis (FMECA) used in functional level. For conducting FMECA in a functional level, a functional description of the system under study is the starting point. In the case of WEC devices, the functions can be described following the energy flow - from ocean waves through the WEC's energy transformation systems all the way to electric power generation and grid connection.

The system functional description describes the functions, their connections and the equipment that are required to perform the functions. In our approach, the functional descriptions are made by using

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Functional Block Diagrams (FBDs) according to the Structured Analysis and Design Technique (SADT) (Marca and McGowan, 1987). A basic block of SADT is illustrated in Figure 3-3.

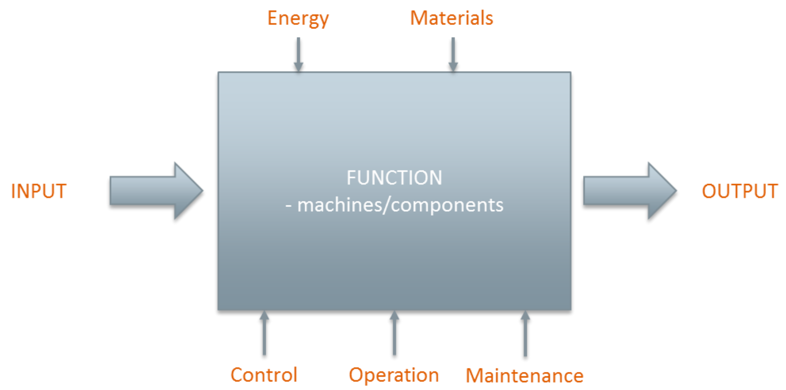

Figure 3-3 A generic functional block of SADT.

An overview of a functional description depicting an OWSC type WEC system with a hydraulic PTO is presented in Figure 3-4**Error! Reference source not found.**. Each of the functions can include several sub-functions, which are all represented using separate SADT functional blocks.

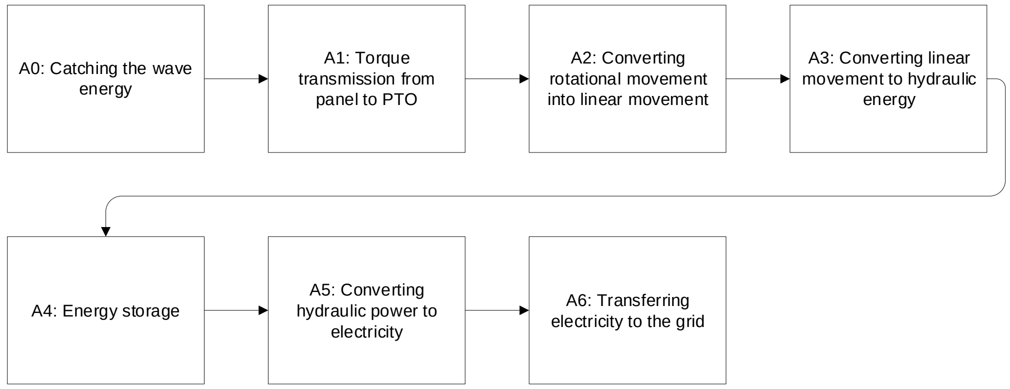

Figure 3-4 A generic functional description of an OWSC device with a hydraulic PTO

3.6 FMECA analysis

Failure Modes, Effects and Criticality Analysis (FMECA) is a reliability analysis method. The overall process of FMECA is described in IEC 60812:2018 (Ed.3.) standard: "Failure Modes and Effects Analysis (FMEA and FMECA)". FMECA can be used in various ways dealing with different level of details. A generic FMECA process is illustrated in Figure 3-5. The purpose of failure modes and effects analysis (FMEA) is to identify how items or processes might fail to perform their function so that any required treatments could be identified.

According to the previous experiences from industrial applications, it is advisable to utilize FMECA on at least two system levels: on functional and on component level. It is useful for the overall system

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development process to start FMECA process on functional level in early phases of the project. In the early phase, the alternations and modifications to the design are much cheaper to conduct comparing to the situation later where some of the critical components are already ordered or the manufacturing process of parts has begun. On functional level, it is possible to analyse large technical systems in a reasonably short time. In the functional level analysis, the failure modes must be kept at functional level. For example, a function will not be executed or a function is being executed incorrectly. Technical aspects come up as possible causes of the functional problems.

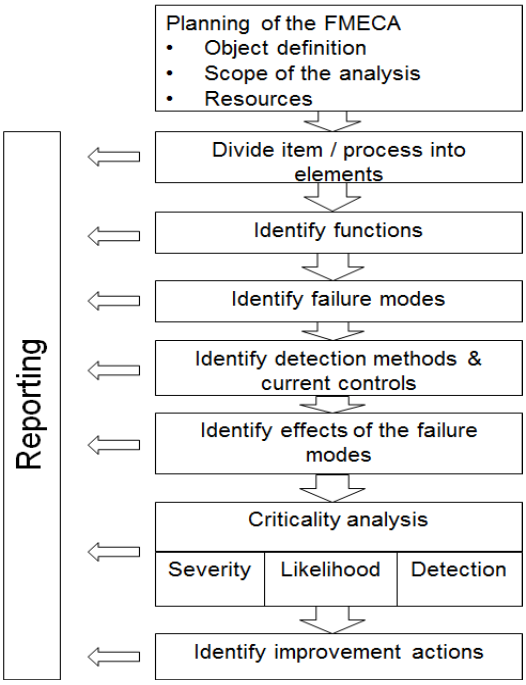

Figure 3-5 FMECA process (adapted and simplified from IEC 60812: 2018 (Ed. 3)

FMECA can be conducted by an individual person, e.g. by a designer, but usually the analysis is conducted as a group work. The participants of the analysis typically include:

- leader of the analysis who leads the discussion
- secretary who writes down the notes
- designers of different subsystems (e.g. mechanical, electrics, automation)
- maintenance experts
- user representatives

The analysis proceeds according to the division principle used. In functional analysis, the system is analysed function by function following the functional description prepared before analysis. The identified scenarios are written down by the analysis secretary on an analysis sheet which usually includes the following columns:

- ID number, refers to functional description or other division principle used in analysis
- Name of the component or function
- Failure mode; there might exist multiple failure modes for single function or component, all these should be analysed on separate rows.

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- Effects of the failure; this might include effects on several levels like on a component level or system level.
- Means for detection; interesting especially in cases when the failure detection must be done via remote connections, use of human senses is impossible.
- Current preventive measures; which mitigating actions already exists.
- Improvement actions; what can be done to decrease the risk
- Criticality assessment: classifications for severity of consequences, probability of occurrence, ranking for detection and various indexes, e.g. Risk Priority Number (RPN) to sort the scenarios according to their criticalities.

A typical FMECA worksheet is presented in Table 3-1.

Table 3-1. A typical FMECA worksheet with columns for criticality assessment.

1	Subsystem, function, item number	Failure mode	Effects of failure	Cause(s) of failure	Means for detection	Current preventive measures	Improvement actions, additional information, remarks	Severity	Occurrence	Detection	RISK (SxO)	OxD	S*D	RPN (SxOxC)
2														
3														

Criticality assessment can be accomplished in many different ways. The most common way is to assess risks by the severity of consequences and the probability of occurrence of the failure scenario. In WEC applications installed onto seabed, also the detection is ranked, because it is very important to get remote information of the failures in short notice, preferably some time before the failure affects the performance. Failures that remain hidden can lead to more serious problems as in that case there might be two failures at the same time if some other component fails while the other remains hidden.

The most important thing in criticality assessment is to get the scenarios into desired order for prioritizing improvement actions. The actual ranking, number, class etc., cannot be used for comparing different analyses against each other, the ranking is valid only in the analysis it is used and the main purpose is to prioritize the identified risks of a single analysis.

The classifications developed for FMECA of the MegaRoller PTO are presented in Table 3-2. There are 6 classes for severity, 4 classes for occurrence and 3 for detection. All these classes have points, which are used for calculating different indexes. RPN is calculated by multiplying all classes together, i.e. severity x occurrence x detection. More usual risk index that does not include detection can be calculated by simply by multiplying severity with occurrence. Of course the classifications can be used category by category without any calculations; e.g. detection rating is useful as such when improvements for automation system are considered.

Usually the most demanding phase of criticality assessment is the estimation of the occurrence. In most of the cases the severity can be assessed quite reliably by the drawings and plans and also the detection can be concluded by the system descriptions. Especially in new solutions like MegaRoller, where the amount of experiences gathered in real-life conditions is limited, estimations are difficult to make. In these situations data from another applications of the same kind of functional part or component can be utilized.

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Table 3-2. Classifications used in MegaRoller FMECA criticality assessment.

Severity		
Effect	Criteria	Points
Environmentally hazardous	Illegal consequences to environment or humans, environmental or safety hazard	10
Very high	Cause a permanent total loss of performance, cannot be recovered remotely, needs maintenance onshore OR minor environmental consequences	8
High	Cause permanent major loss of performance (> 50% decrease of performance), cannot be recovered remotely, needs maintenance onshore	7
Moderate	Cause permanent partial malfunction of a PTO (< 50% decrease of performance), the problem cannot be recovered remotely, needs maintenance onshore	5
Very low	Cause temporary/partial/short loss of PTO performance, can be recovered remotely without onshore maintenance	3
Minor	Cause a minor nuisance: can be overcome with no production losses with remote operations	1

Occurrence		
Probability of failure	Criteria	Points
High	Occurs more than once during the maintenance period (5 years)	10
Moderate	Occurs once in 5 years (occurs during every maintenance period)	7
Low	Occurs 1-2 times in the system lifetime (20 years).	3
Remote	Less than once in 20 years (not likely to occur during the system lifetime).	1

Detection		
Easiness of detection	Criteria	Points
Impossible	The failure remains hidden, and/or it cannot be detected before it affects the system performance.	10
Remote	The failure detection requires an expert to analyse data, it cannot be detected automatically by the control system before it affects the system performance.	5
High	The failure can be detected automatically by the control system.	1

If the functional level FMECA shows that some functional failure modes are critical for the system performance, it is well justified to continue analysis with component level FMECA. In the component level FMECA, the modules or parts are analysed in details. This way the most critical component and their connections are identified. By this two-stage FMECA process, it is possible to allocate expert resources appropriately and to target the reliability improvement measures cost-effectively to the most critical components. FMECA results are also essential information when building a maintenance program according to Reliability Centred Maintenance (RCM) principles (IEC 60300-3-11:2009).

According to standard IEC 60812, the FMECA report should include the following information:

- description of the system
- description of the scope and the boundaries
- criteria used to define when treatment is needed
- assumptions, use scenarios
- description of the methodology
- identification stakeholders and personnel involved
- description of the method used for criticality analysis
- sources of data, references to materials used
- identification of failure modes, effects, criticality and causes
- summary of the results
- limitations for the future updates
- design changes already incorporated in the item
- analysis records

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3.7 Reliability modelling method utilizing reliability block diagrams

In reliability engineering, system reliability predictions can be performed using various methods. Some of the most widely used methods include Reliability Block Diagrams (RBD), Fault Tree Analysis (FTA), and Markov models (Verma, et al., 2010). Sometimes analyses can also include a combination of different methods. The selection of a suitable modelling approach should always be done considering the application at hand. In our approach regarding the MegaRoller WEC device, we apply a reliability modelling and simulation approach utilizing RBD. This approach was selected based on the following factors:

- RBD is generally used to identify parts of the system that are weakest from the reliability perspective. Thus, in development of a new technology, it can be used to direct engineering activities to the system elements where reliability improvements have the largest impact on the overall system reliability performance.
- RBD provides a visual, easy to understand representation of the system, which is typically useful in communication of reliability aspects in new technology development.
- RBD is a method mainly used for non-repairable systems. In the MegaRoller case, this means that the PTO system is not subject to continuous maintenance activities. However, system elements can be replaced or maintained to “as good as new” condition in periodic maintenance operations, which can be incorporated in a RBD model.

The application of RBDs in reliability analysis is defined in the international standard IEC 61078:2016 Reliability block diagrams. A RBD describes a system as a combination of interconnected blocks, each representing a defined part of the system, typically a component or a group of components. The blocks are connected so that they represent the system’s success logic, which may not necessarily need to be similar than the schematic or physical construction of the system. Each block is assigned with a probability distribution describing the block’s reliability performance over time (Čepin, 2011; Verma et al., 2010). The applicable reliability distributions that can be applied to the individual components include, but are not limited to, the following (ReliaSoft, 2015):

- Exponential distribution: A simple model that represents a constant failure rate, and is applicable mainly for certain electronic components.
- Weibull distribution: A general model widely used in reliability engineering to represent the reliability performance of various electronic and mechanical components, equipment or systems.
- Lognormal distribution: A general model widely used in reliability engineering to represent components with cycles-to-failure characteristics, with failures related to fatigue and insufficient material strengths.

In practice, RBDs are usually created using computer software. Several commercial software packages are available for performing RBD calculations. Key concepts of RBD are visualized in Figure 3-6.

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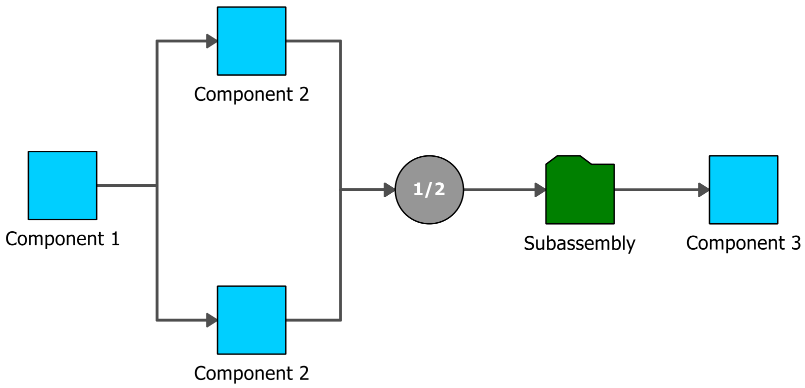

Figure 3-6 Key elements of a RBD, with different types of elements distinguished by different colours

In Figure 3-6 blue blocks represent system components, which can be in series and parallel arrangements. In parallel arrangements, nodes (grey circle) are used to describe the number of functional paths required through the node for the entire system to remain operational. RBDs can be built hierarchically using subassemblies (green block).

The RBD method is flexible and can be applied in different phases of design and validation. It can also be done on different levels of detail. For WEC design, it can be applied throughout the system development process. In concept design phase, some rough reliability estimations can be made based on a RBD model from the very early stages of development. For example, this can be used to support comparison studies between fundamental design choices, such as comparison between hydraulic or electric power transmission alternatives. Reliability modelling can also be used to allocate reliability requirements between different subsystems, and to identify clear bottlenecks in the system concept related to reliability, as well as maintainability and availability. In addition to examining individual WEC devices, modelling can be also done on a level of a WEC farm consisting of multiple units.

In the system design phase, the reliability model should be updated as the system design proceeds. This allows more detailed reliability estimations and further evaluation of design alternatives. FMECA results can be used to direct the modelling activities so that the identified most critical parts of the system are examined and simulated at the highest level of detail. An important output of the reliability simulations is the identification of components and subsystems, which have high uncertainty in their reliability performance. This information can be used to indicate which parts of the system still require modifications to ensure sufficient reliability and which part require most thorough testing activities. After system modifications, the model must be further elaborated to represent the actual design.

Being mathematical models using probability distributions, RBDs are representations of data. The quality of models is always dependent of the amount and quality of data available. Thus, important research tasks considering WECs are to define the reliability distributions for different system components, and to study uncertainties associated with new product development project in a challenging environment. A perfect reliability calculation can never be achieved, but a number of data sources can be utilized to provide a credible estimation of system reliability. These data sources include:

- Data provided by component manufacturers
- General reliability data sources, such as industry guidelines, handbooks, standards, and databases
- Analytical results regarding component lifetimes (especially with tailor-made system components)
- Relevant experiences from previous installations
- Reliability testing, which can include e.g. accelerated testing.

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While comprehensive reliability data can only be obtained through a number of tests, credible reliability predictions can be created in engineering applications using a combination of the above-mentioned data sources.

3.8 Reliability model and reliability simulations of the PTO system

In the MegaRoller project, a reliability performance model of the PTO system is defined and created using RBDs in ReliaSoft BlockSim software tool. Specifically, the simulation capabilities of the software are utilized (in contrast to creating an analytical RBD). This allows high flexibility to the modelling, allowing for example considerations related to periodic maintenance of the device.

As key documents in model development, MegaRoller system design documents are utilized. Mainly, the model is used for simulating the system reliability behaviour over time, and evaluating the achievable reliability performance level of the system design. It can also be used to compare various design alternatives from the perspective of reliability. A high level RBD representation of the MegaRoller system is presented in Figure 3-7.

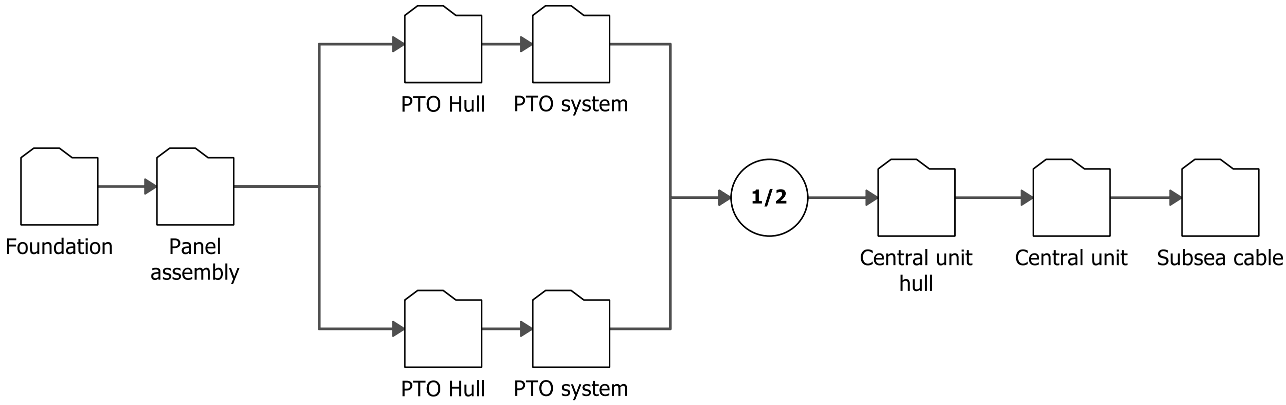

Figure 3-7 A high-level RBD representation of the MegaRoller concept.

The PTO system reliability model is constructed and updated according to the design changes and implementation decisions done in the project. The main modelling activities will focus on the PTO system, which consists of several subsystems. Based on the data on reliability parameters regarding the different elements in the PTO system configuration the simulator based validation defines the confidence of achieving the stated MegaRoller design targets.

Reliability modelling utilizing RBDs is expected to yield the following results:

- Estimation of the reliability performance of the entire PTO and its subsystems over the expected system lifetime. This can be provided using a combination of different metrics, such as point reliability (the probability that the system will remain functional at a certain point of time), or mean time to first failure (MTTFF). The development of failure probability over time can also be represented graphically.
- Identification of the components that have the largest impact on the overall system reliability. This can be represented using the Failure Criticality Index (FCI), which describes the criticality of individual components by showing the percentage of times that a failure of this component caused the entire system to fail.

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- In addition, the results can be used in combination with the LCC analysis, to estimate the costs related to component failures and periodic maintenance.

Criteria for the evaluation of system reliability performance are based on the requirements set for the reliability performance of the MegaRoller PTO design. The results of the reliability modelling activities form a part of the overall system reliability performance evaluation and validation.

The results of the reliability performance simulation activities will be documented as a reliability performance simulation report. The contents of this report will contain at least the following aspects:

- Description of the RBD model structure of the target system.
- Description of the probability distributions and their parameters used to describe the reliability characteristics of individual components. This includes justification of why the selected reliability distribution was used, and what data was used to determine the distribution parameters.
- Estimated reliability performance of the entire PTO and its subsystems over the expected system lifetime.
- Listing of the most critical components and subsystems in terms of their impact on the overall system reliability performance.

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4 ASSESSMENT OF ENVIRONMENTAL AND SOCIO-ECONOMIC ASPECTS

There is an increasing recognition of the importance of streamlining the EIA process framework of the wave energy sector across different countries to understand the potential impacts of a device in early stages of its development. The fact that wave energy projects have unique characteristics, different from any other marine projects, results in a lack of methodological approaches for environmental and socio-economic impacts evaluation.

Table 4-1 shows the main receptors to take into account when assessing the environmental and socioeconomic impacts of Marine Renewable Energy (MRE) projects. The detailed information can be seen in D2.6 'Environmental Impact Assessment (EIA) and Socioeconomic Impact Assessment (SEIA) models'.

Table 4-1 Main environmental and socioeconomic factors.

Factor	**Receptor**
Physical	Hydrodynamics
	Water Column
	Seabed
	Shoreline
Biological	Benthic habitats and communities
	Fish and turtles
	Marine mammals
	Birds
Socioeconomic	Local communities
	Archaeological/protected sites
	Landscape/seascape
	Economic activities

4.1 Environmental Impact Assessment (EIA) and Socioeconomic Impact Assessment (SEIA) tool

The EIA tool initiated within the MegaRoller project works as a recommended practice for regulators and managers on best monitoring techniques for nearshore based wave energy projects and considers both environmental and socioeconomic aspects. The methodology (Figure 4-1) adopted focuses on the scoping phase, whose goal is to identify the most relevant key environmental issues. These include environmental receptors potentially affected by the project, potential impacts of the project on the environment, methodologies to use and possible mitigation measures. The proposed methodology, summarized below, is described in details in the above mentioned deliverable 2.6 of the MegaRoller project.

An exhaustive literature review was carried out in 2018 between July and October on previous EIAs for similar installations. In total, 24 relevant studies were analysed. Data collected was then gathered in three matrices – physical, biological and socioeconomic factors – by crossing the interactions between relevant receptors and stressors resulting in a matrix of key effects.

The matrix analyses the key effects on receptors throughout construction, operation and decommissioning phases, taking also into account the preparatory phase and accidental events. Among others, the main stressors considered relevant in the model are the following: vessel activity, sampling, dredging activities, drilling activities, chemical pollution and physical presence of equipment.

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These key effects were then categorised based on the classification provided by European Marine Energy Centre (EMEC) – major, moderate, minor, negligible, positive and 'no interaction'. Whilst an impact may be deemed minor for an individual device, it could potentially translate in a major impact when considered cumulatively or combined with the impacts of other devices or marine uses. Hence, minor impacts are also included in the identification of best monitoring activities along with major and moderate impacts. After choosing which development phase and receptors to analyse, the user is guided through the steps of the tool, from the impact evaluation to the choice of monitoring parameters. The final output will be a list of recommended monitoring practices.

This tool will be further developed to inform on activities schedule and planning. Following an Adaptive Management (AM) approach the user is encouraged to reuse the tool to readjust management actions throughout the project's life cycle as learning occurs trough monitoring.

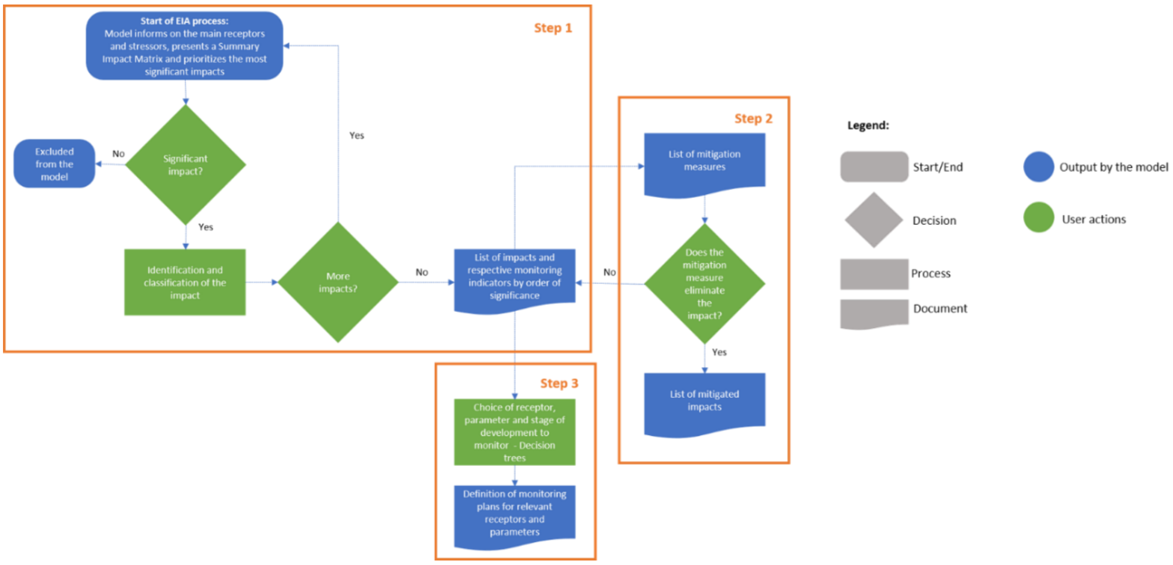

Figure 4-1 Flowchart for proposed tool.

4.2 Environmental Impact Assessment (EIA) and Socioeconomic Impact Assessment (SEIA) of the MegaRoller device

The EIA method developed in this project will be validated through its application on the final design of the MegaRoller device considering also the project's characteristics and the site sensitivity. Further on, based on the set of key effects a monitoring plan will be delineated considering the following criteria:

- nature of the key environmental and socio-economic effects identified,
- physical features and sensitivities of the site,
- project characteristics.

The methodology steps will be part of a multi-criteria tool to decide on best monitoring activities schedule and methods. The tool will be validated through its application on the MegaRoller device and on its possible locations.

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In most cases, the early stage of wave energy technologies lacks information on the impacts on the environment and thus the decision is risk based relying on the implementation of mitigation measures and on the results of monitoring activities. In this sense, an Adaptive Management (AM) procedure will be adopted to consider mitigation measures' adaptation and monitoring plan review as new data is collected.

4.3 Life cycle assessment (LCA)

LCA is a valuable tool that allows the assessment of the cumulative environmental impacts of a system over space and time throughout its life cycle from cradle to grave i.e. from the extraction of raw materials until its disposal (EC-JRC, 2010). Each stage of the life cycle is analysed in detail and data on the energy, materials, emissions and waste products associated are gathered. Justifiable assumptions are made when such information is not available.

The LCA results are described as a set of identifiable consequences or impact categories. This methodology complies with international standards ISO 14040, which specifies the general framework, principles and requirements for conducting and reporting this type of assessment (ISO 14040:2006). The standard describes the LCA as comprising four main stages (Figure 4-2):

- Goal and scope;
- Inventory analysis;
- Impact Assessment and
- Interpretation.

This analysis has the purpose of analysing the components, materials or stages of the life cycle with the most significant environmental burdens. LCAs can help engineers and designers in the decision-making process regarding product design.

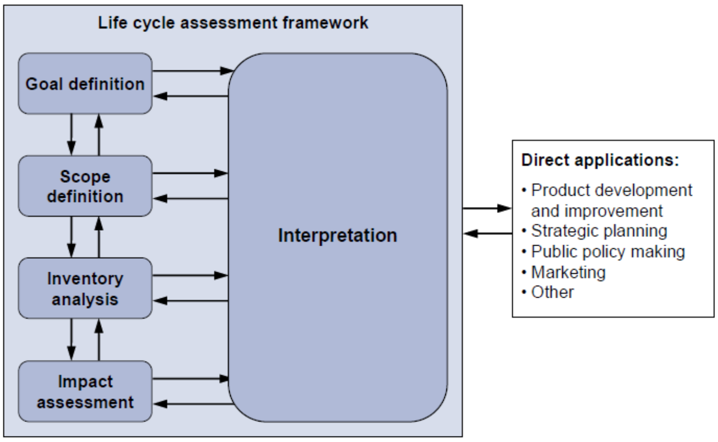

Figure 4-2 Life Cycle Assessment framework (ISO 14040:2006; modified)

According to (Curran, 2015) there are four different types of LCA, depending on the goal of the analysis:

- Single system, results for internal use: assessment of a finished product to further search for opportunities to reduce its environmental impact;
- Single system, results for external use: disclosure of the environmental impacts of a product to the public;
- Comparative analysis, results for internal use: comparison of different designs or manufacture processes with the aim to assist on decision making;

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- Comparative analysis, results for external use: results disclosure to the public on the environmental impact of a certain product of to advocate about possible legislations or bans affecting the product.

The deliverable D2.4 ‘Preliminary LCA Report’ contains a detailed description of the LCA methodology.

4.4 LCA of the MegaRoller device

A preliminary LCA has been carried out on a set of early design concepts using the software tool SimaPro to support the design phase decisions on the most appropriate option for the PTO system from an environmental point of view, focusing mainly on the Global Warming Potential (GWP) impact category.

When data is not available, assumptions or other options for data collection have been discussed together with project partners. Life cycle phases and materials with the most significant environmental impacts will be identified through a sensitivity analysis and changes in the processes and material choices will be suggested.

The following activities have been conducted in the project:
- Definition of impact assessment method
- Definition of data sources and methodology for data collection
- Data requirements listing
- Data collection from project partners
- First LCA for the set of early design choices

The LCA carried out for an early design of the device proves the results are aligned with all previous studies on MRE technologies in concluding the main environmental impacts are due to materials use and manufacture, while Assembly and Installation (A&I) and Operation and Maintenance (O&M) do not show significant impacts. The impact of manufacture is mainly due to high amounts of material used, particularly steel. End-of-Life stage is currently excluded from operational boundaries of the majority of MRE developments and its inclusion in eco-design initiatives is challenged by uncertainties on a temporal, technological and business level such as uncertainties regarding recycling ratios. Additionally, this report corroborated with previous LCAs on ocean energies by proving the importance of the End-of-Life scenario to the overall environmental performance and highlighted the need for further efforts to better understand how to model this stage. The preliminary LCA results are reported in the deliverable D2.4 ‘Preliminary LCA Report’.

The LCA application version developed in the project will be adjusted to the final design version of the MegaRoller device and the results will be compared with other marine renewable energy technologies as well as the other traditional means of generating electricity (i.e. using fossil fuels). The final LCA of the MegaRoller device will be developed through the use of the LCA software package SimaPro.

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5 ASSESSMENT OF LIFE CYCLE COSTS (LCC)

Wave energy has great potential as a renewable energy resource. From the cost point of view, it has been estimated that improving technology and economies of scale will allow wave generators to produce electricity at a cost comparable to other forms of renewable sources e.g., wind-driven turbines (Ocean Energy Council, 2020). Table 5-1 shows the operational figures of the current estimated costs and cost projections for wave energy until 2050 (IRENA, 2014).

Table 5-1 Cost figures of wave energy (adapted from IRENA, 2014)

	Source	2010-2012	2020	2030	2050
Capital cost of farms (€/kW)	IEA	5 650	4 070	3 350	1 750
	UK	5 000- 9 000	3 000-5 000		2 500 - 3 000
	ETI[a] / UKERC	4 840 - 9 680	2 723 - 4 235	2 118 - 2 723	1 513 - 2 118
Operation and maintenance cost (€/kW/year)	IEA	86 (projected to decrease to 47)			
	ETI / UKERC	48 - 97	30 - 73	18 - 30	12 - 24
Total electricity production cost (€/MWh)	IEA	286	207	172	
	UK	213 - 500		113 - 226	88 - 125
	ETI / UKERC	242 - 605	121 - 242	85 - 121	61 - 97
Average levelized cost of energy per MWh	E&Y	505	268	148	108
	SI Ocean	330 – 630[b]	280 – 350[c]	150 – 180[d]	

[a] The roadmap targets from ETI/UKERC apply to both tidal and wave energy. Exchange rate used: 1.21 EUR/Gross Domestic Product (GDP).
[b] Estimates for early arrays.
[c] Assuming deployment rate in the range of 100 MW.
[d] Assuming a deployment rate of around 5 GW.

5.1 Life cycle costing

5.1.1 LCC method

Life Cycle Costing (LCC) was first applied by the United States by the Department of Defense in the middle of 1960s. The LCC was used in the procurement of military equipment, as they found that acquisition costs only accounted for a small part of the total cost for the weapons systems while operation and support costs comprised as much as 75 % (Estevan and Schaefer, 2017).

Since then, various industry sectors, companies, public sector as well as academic actors have been interested in the development and implementation of LCC i.e. assessing the costs that incur during the entire life cycle of a product, service, investment, solution, etc. All the different fields, scopes and aims behind LCC have laid also to a large number of different LCC definitions (see eg. Huppes *et al.*, 2004). According to Fabrycky and Blanchard (1991), LCC includes: *"All costs associated with the product, system or structure as applied over the defined life cycle".*

In industrial applications, LCC typically follows the process presented in the IEC standard on Life cycle costing (IEC 60300-3-3:2017). This standard lays also the groundwork for LCC of the MegaRoller device. According to the IEC 60300-3-3 standard, *"Life cycle costing (LCC) is the process of performing an economic analysis to assess the cost of an item over a portion, or all, of its life cycle in order to make decisions that* *will minimize the total cost of ownership while still meeting stakeholder requirements".* The life cycle costing process consists of five main steps:

1. Establish the organizational context
   – Define context for the LCC case and alternatives to compare
2. Plan the analysis
   – Define scope and objective of analysis, constraints, etc.
3. Define the analysis approach
   – Select of develop an LCC model, define the cost breakdown structure etc.
4. Perform the analysis
   – Collect cost data, perform LCC and sensitivity analysis etc.
5. Finalize the analysis
   – Identify follow-up actions and document analysis

In order to deal with financial, environmental and social concerns, four LCC types have been introduced: fLCC, eLCC, feLCC and sLCC. Conventional LCC assessment that only focus on private investments from one actor is categorized as financial LCC (fLCC). An Environmental LCC (eLCC) builds upon data of fLCC and extends it to life cycle costs borne by other actors. A feLCC is a combination of these two LCCs. In Societal LCC (sLCC) all costs borne by anyone in society, whether today or in the future, and associated with the life cycle of a product are taken into account. (Hoogmartens et al., 2014). These concepts should not be confused with Life Cycle Analysis (LCA) that is internationally standardised in ISO 14040 and 14044. The environmental LCA does not address the economic elements of the product, system, service life cycle, which indeed are the main focus of LCC. (Estevan and Schaefer, 2017)

The lifetime of a wave energy system, e.g. MegaRoller device, could be upward of several decades, which means that operating and maintenance costs can end up being several times higher than the original capital cost (Figure 5-1). For example, predictability of the remaining useful lifetime of the PTO components plays an important role in achieving the goals for reducing the need for periodic maintenance as well as downtime due to failures and negative environmental impacts. In addition, it should be considered that the major part of life cycle costs is committed already in design phase. Thus, the highest value from life cycle costing is achieved early in the life cycle when possibilities to influence technical design of the solution and future costs are the greatest.

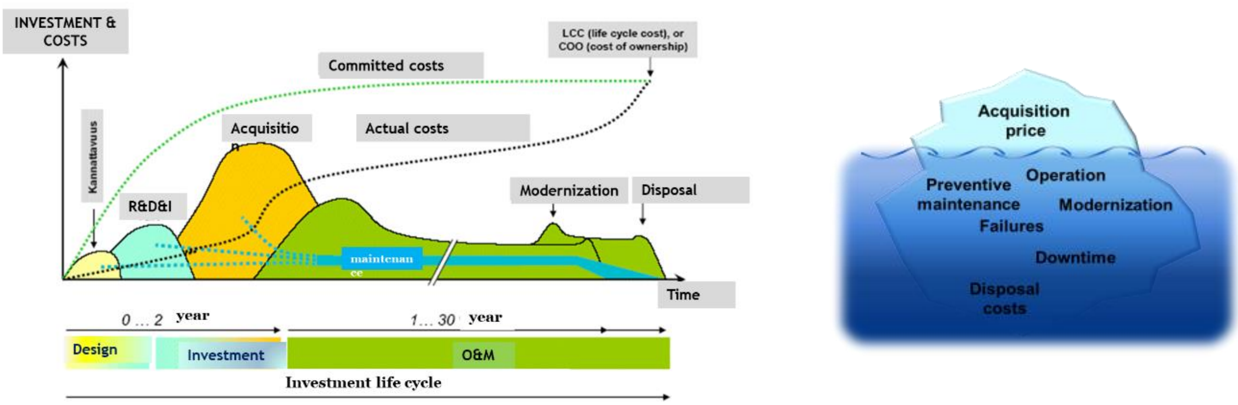

Figure 5-1 The LCC perspective to the costs (adapted from Järviö, 2014).

5.1.2 LCC estimation of the MegaRoller device

In the MegaRoller project, "economic evaluation" refers to the appraisal of financial and economic performance of the MegaRoller device. The objective of the life cycle costing in the MegaRoller project is to define and to assess all the costs that the novel technology generates during its entire life cycle. The

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analysis follows the guidelines given in the IEC 60300-3-3 standard where the financial LCC linked with FMECA analysis. This means that economic evaluation and technical reliability assessment are combined to be able to give input for the optimization of operational efficiency and reliability and minimizing life cycle costs of different MegaRoller design concepts.

Early implementation of cost analysis models influences the design changes of the device and provides explanations of the relationships between cost and design parameters. It contributes to cost reduction by identifying high cost contributors and supports the designers to make transparent, systematic and reliable decisions as it creates a common understanding of the impacts of the various design options before the actual decision takes place.

MegaRoller LCC	
What –	To support design and investment decisions on MegaRoller device
Why –	To make different aspects affecting decisions visible To demonstrate MegaRoller costs throughout the entire life cycle of the device
Who –	Technology providers' design and business development representatives. Managers responsible for investment planning, marketing and sales.
When –	Especially in the early phases of the design process and investment decision-making

To sum up, the main role of life cycle cost assessment in MegaRoller can be seen as:

- Providing life cycle cost as an input to the study on industrial business cases where the Levelized Cost of Energy (LCOE) is calculated.
- Supporting the concept phase decisions from economic point of view when comparing cost effects of different solutions. In concept phase the changes are easiest and cheapest to do.
- To estimate the life cycle costs of the final design of the MegaRoller device

The aim of life cycle cost assessment is not to find the cheapest option but a good balance considering all decision criteria e.g. safety, reliability, maintainability, sustainability, cost, energy production capacity.

5.2 LCC steps in the MegaRoller

Evaluation is an essential phase of the design and decision-making processes as it provides a link between the generation of proposals and the actual decision. Economic evaluations involve the identification, measurement and valuation, and then comparison of costs of two or more alternatives. (Räikkönen *et al.*, 2016). In the MegaRoller project, the costs and consequences of alternative design and O&M (operation and maintenance) scenarios are compared to examine the best use of the resources. The MegaRoller LCC framework and process consists of several steps which are presented in Figure 5-2. In addition, based on the LCC method and process, a prototype tool that enables LCC of the MegaRoller device was developed (Figure 5-3).

Analysing the life cycle costs of different WEC concepts is not a simple task. The first challenge is to establish a structure, which includes all relevant cost elements, factors and their effect on total life cycle cost of the WEC concept. Another challenge concerns the availability of data for costs. Especially, as the analysis is done in the early phases of a life cycle, uncertainty related to costs is high. Thus, a tool

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supporting the LCC analysis could be of help and the LCC demo tool that is developed in the MegaRoller project strives to tackle the aforementioned challenges.

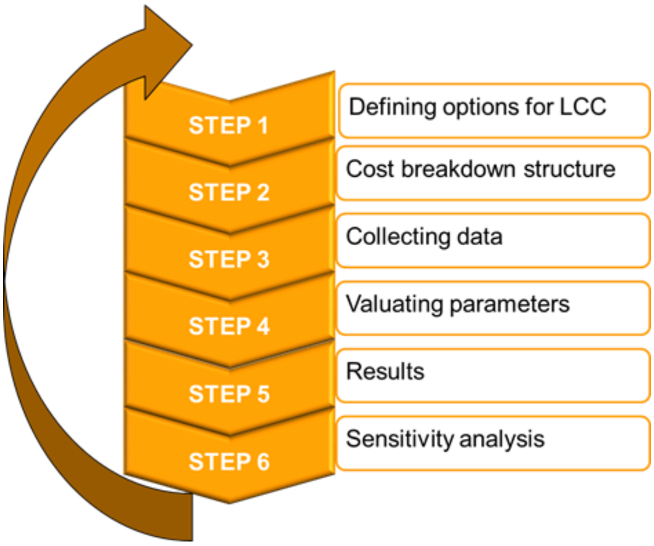

Figure 5-2 LCC steps in the MegaRoller project following the standard IEC 60300-3-3.

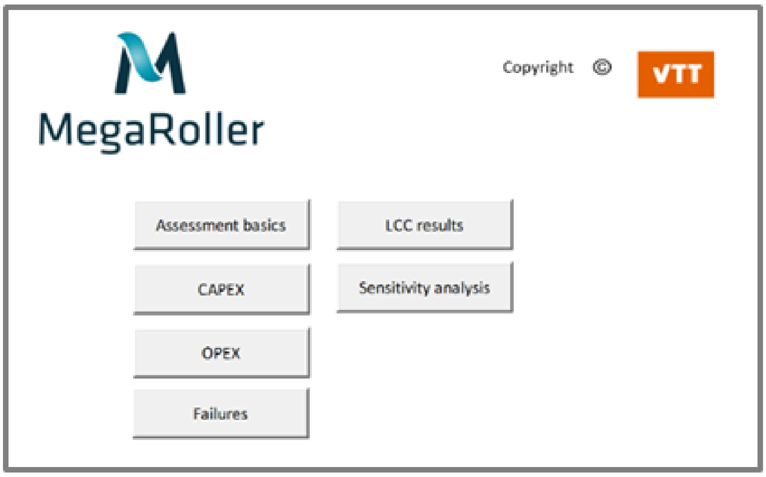

Figure 5-3 Home screen of the developed LCC prototype tool.

In step 1. 'Defining options for LCC' the aim is to clearly define the scope. The term "scope" means aspects, such as why an business case proposal is proposed, whose costs count, as well as the technology and operational environment specific information, calculation parameters, the scope of the activities to be modelled, etc. All the assumptions and boundaries of the analysis need to be defined as well.

Step 1	Structuring the business case and solution to be assessed	Which solution(s) do you want to assess? MegaRoller device What is the designers' need? Who are the decision-makers? In which phase of the design and decision-making process will the assessment be conducted? Which is the viewpoint of the assessment? Whose costs count? Which major stakeholders are likely to be affected?

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Time span / calculation term	The term “Time span / calculation term” refers here to the number of the years to be applied in the evaluation. In other words it is a time horizon for the calculations. Determination of a calculation term can be based, for example, on the MegaRoller devices’ functional lifetime, physical lifetime, technological lifetime, economic lifetime or social lifetime.
Starting year for calculation	For example, a calculation starts in the beginning of the year 2020.
Currency unit	Different alternatives €, $... etc.
Discount rate	The discount rate (%) typically refers to the required rate of return on the investment capital. It can also be seen as the cost of capital. Different discount rates apply to different organisations to different situations. Using the discounting is important in the assessment because it facilitates the translation of future economic value to present value.
Electricity production	Array Annual Energy Production (MWh).

Step 2 ‘Cost breakdown structure’ focuses on the identification of the costs and the development of the cost breakdown structure. In order to estimate LCC of the MegaRoller device, it is necessary to first divide the costs for applicable costs categories. The proposed categorisation can be used as the default structure and the basis when assessing LCC. In this phase, also the reliability validation of the PTO and the results of the FMECA are considered (see Chapter 3).

Step 2	Cost breakdown structure, failure identification (FMECA)	Can costs be categorised somehow? Which costs of the MegaRoller device are typically relevant, which are not? (i.e. “high cost and benefit items”, risks)? How about the reliability and failure costs related to MegaRoller and its usage?

Ocean Energy Systems (OES) have assembled cost data from many different developers. The information presented in Figure 5-4 shows that device costs and OPEX dominate the costs for wave energy devices. However, there are other important factors (grid connection, moorings and foundations) that contribute to project costs. However, this data include data from many different device types, so it serves as a guide rather than something applicable to all technologies. (World Energy Council - COCME, 2015)

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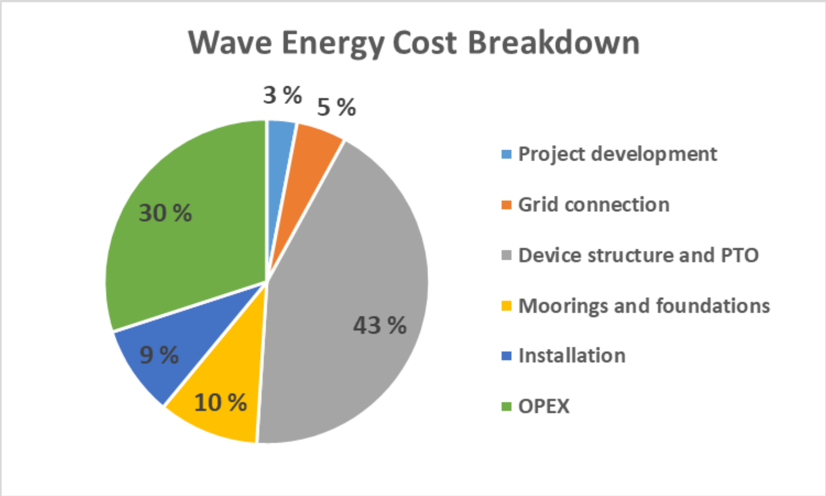

Figure 5-4 Wave energy cost breakdown (World Energy Council - COCME, 2015)

The main costs related to the MegaRoller are capital costs CAPEX (MegaRoller device cost, installation etc.), operating and monitoring (remote operation cost, scheduled inspection, consumables etc.) maintenance (scheduled annual maintenance cost, service maintenance cost and unavailability cost etc.) OPEX and other costs. The cost breakdown structure developed for the MegaRoller project is illustrated in Figure 5.4. The cost hierarchy can be the backbone when comparing economic effect of defined scenarios and also structures cost data collection for cost part of LCOE calculation. The high-level hierarchy will be complemented by details during the project.

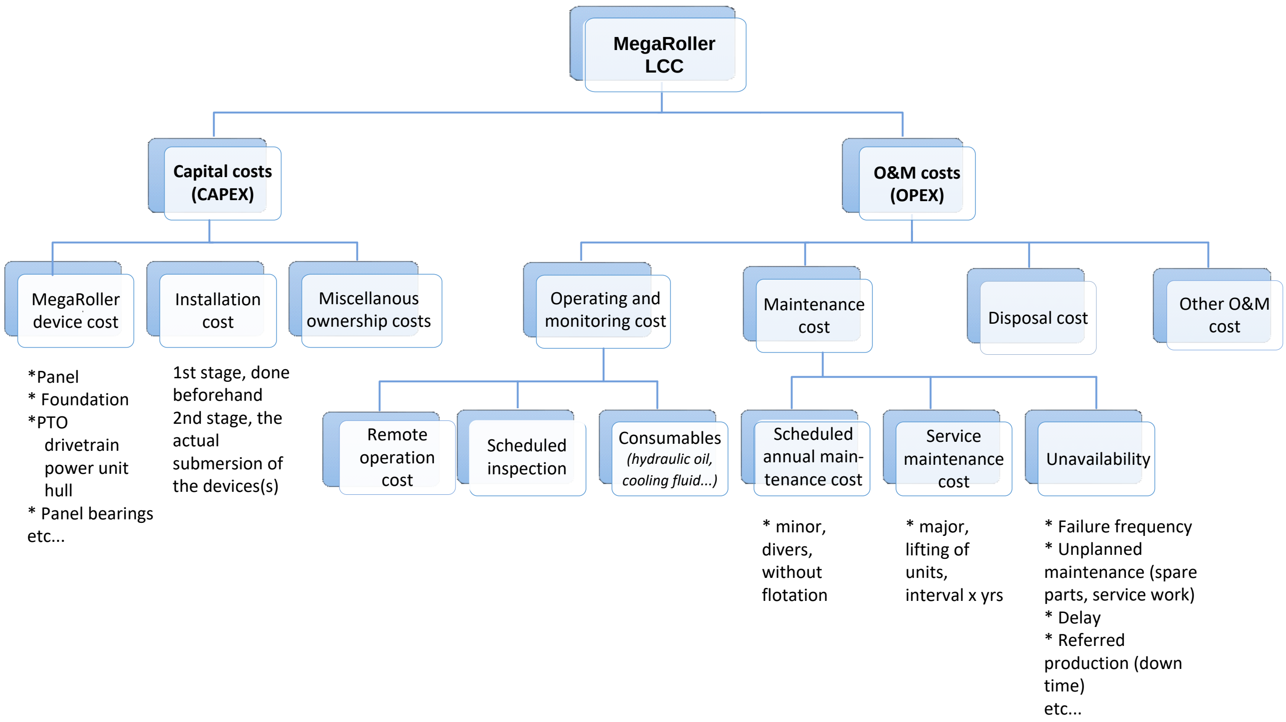

Figure 5-5 MegaRoller cost breakdown structure (CBS)

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Regarding the identification and valuation of preventive and unplanned corrective maintenance costs and unavailability, there is a clear linkage between economic aspects, risk and reliability issues. For an operator of MegaRoller, it is important to maximize the uptime of the asset and to keep the system continuously operational. Reliability issues and scheduled maintenance periods interrupt the operation and eat the earnings of the business. It should also be considered that e.g., technological failure situations that could lead to the occurrence of environmental risks are generating impacts to all stakeholders (see also Chapter 4). Direct maintenance costs can also get expensive and should therefore be minimized. Thus, it is important to optimize the need for the scheduled and service maintenances and (both spare parts and service work), and to reduce the downtime due to failures and negative environmental impacts. In all, the evaluation of the wave energy applications is about balancing out values emerging from different domains: environmental, technological, economic, business and societal.

Figure 5.5 presents the information used to quantify failures in one of the prototype tool's modules. Categorization and assessment of failure risks and risk related costs helps to calculate potential cost savings achieved by failure risk reduction. The failure costs include both unplanned maintenance costs (spare parts and work) and unavailability costs. Probability is calculated based on the risk frequency (risks realized during the life cycle). Annual cost savings are calculated by multiplying the occurrence and the cost and dividing this by the lifetime (years).

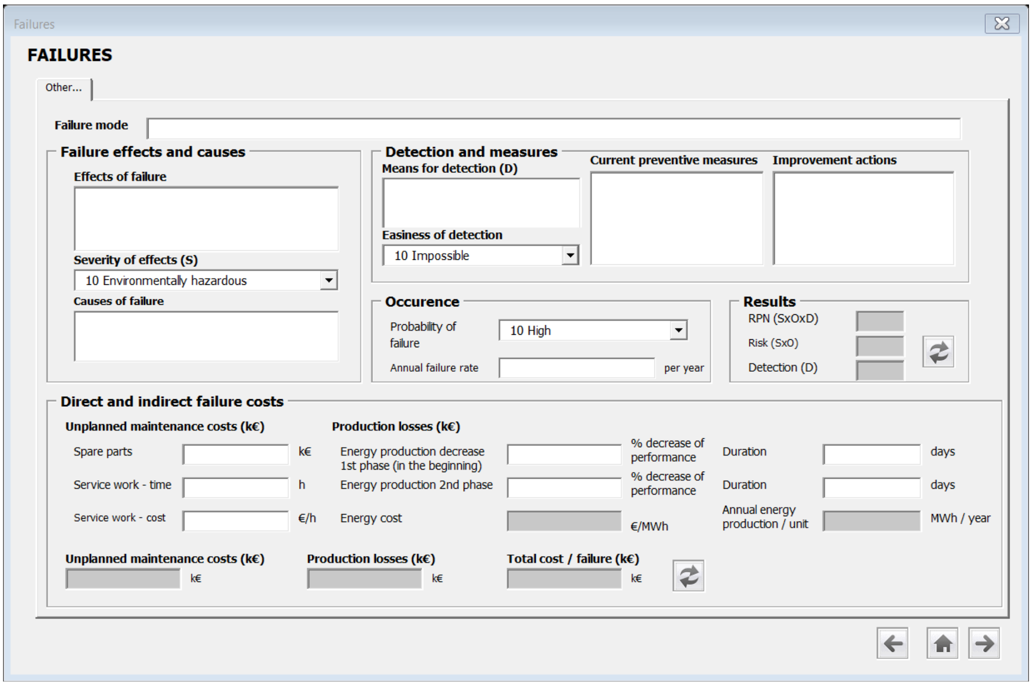

Figure 5-6 MegaRoller LCC tool: Failures –user interface.

In step 3. 'Collecting Data' LCC requires wide variety of data which can be collected from different kind of data sources. Detailed data collection process needs to be defined when data needs are specified in steps 1 and 2. The main issue in data collection is to ensure the quality of data which will be used in calculations. Quality and reliability of LCC results are correlated to quality of data used in evaluations. High data quality needs to be emphasised when planning data collection.

Data with good quality is the main objective of data collection step. Some data collection methods can be very expensive and time consuming when practical reasons lead to compromises in data collection and quality. When compromises are necessary decision maker need to be aware which data quality dimensions

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are decreased. On the other hand it is good to remember that high quality data is not always the most accurate for example. Decision-making situation inherently includes lot of uncertainties which cannot be removed and thus is not worth putting efforts to collect data with high precision when needed information can be produced even with inexact data. When planning data collection, relevancy dimension should be carefully considered as it can reduce data collection efforts.

Step 3	Data collection • Cost, non-monetary data • Other calculation parameters, • Failures: consequences & probabilities	What are the main data sources for monetary costs? How could the data on intangible criteria (i.e. non-monetary value elements) be collected? How about the reliability related data? Calculation parameters: What is the typical time span/calculation term for the evaluation? What discount rate(s) do you typically use? Why? Etc.

Kahn et al. (2002) have presented a list of 16 items describing dimensions of information quality. The list, which is presented in Table 5-2 can be also applied to assess quality of potential data sources for the MegaRoller LCC.

Table 5-2 Dimensions of information quality (Kahn, Strong and Wang, 2002).

Dimension	Definition
Accessibility	The extent to which information is available, or easily and quickly retrievable
Appropriate amount of information	The extent to which the volume of information is appropriate for the task at hand
Believability	The extent to which information is regarded as true and credible
Completeness	The extent to which information is not missing and is of sufficient breadth and depth for the task at hand
Concise representation	The extent to which information is compactly represented
Consistent representation	The extent to which information is presented in the same format
Ease of manipulation	The extent to which information is easy to manipulate and apply to different tasks
Free-of-error	The extent to which information is correct and reliable
Interpretability	The extent to which information is in appropriate languages, symbols, and units, and the definitions are clear
Objectivity	The extent to which information is unbiased, unprejudiced and impartial
Relevancy	The extent to which information is applicable and helpful for the task at hand
Reputation	The extent to which information is highly regarded in terms of its source or content
Security	The extent to which access to information is restricted appropriately to maintain its security
Timeliness	The extent to which the information is sufficiently up-to-date for the task at hand
Clarity	The extent to which information is easily comprehended
Value-Added	The extent to which information is beneficial and provides advantages from its use

In step 4 'Valuating parameters' monetary values should be given to life cycle costs of the MegaRoller device. Often, for example, engineering and manufacturing estimates for costs are available (market prices); e.g. component and equipment prices. Older estimates available may be updated to the present time of appropriate factors, such as annual discounting and escalation factors. In addition, it should be

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taken into account that comparing cash flows from different periods can be achieved only by incorporating the time value of money (discounting). Although discounting is a generally accepted practice, the applied discount rate is often controversial. In business circles, high discount rates are applied such that current financial flows have a higher weight. In contrast, from a societal or environmental point of view, low discount rates are preferred to avoid the fact that current activities impose large costs on future generations (Hoogmartens *et al.*, 2014).

Through the use of reasonable and consistent assumptions, an estimation of the life cycle costs can be prepared. One should also note that not all of the cost categories are relevant. The preparer is responsible for the inclusion of the costs that will produce a realistic comparison of design alternatives. Evaluation means determining the value or worth of an investment being considered in a specific decision situation. In the MegaRoller project, it involves exploring, understanding and describing the consequences of the MegaRoller device throughout its lifetime.

Step 4	Framework development and testing Result calculations (numerical and graphical)	What are typical decision/ acceptability criteria and measurement indicators you use and calculate? ○ Financial indicators ○ Risk indicators ○ Other How do you make the ranking of options if needed? How the decision is finally made (e.g. based on calculations, visions…)?

In step 5 'Results' several financial metrics may be employed to quantify the economic viability of an ocean energy project. The most relevant key indicators to be calculated and related graphs that are also included in the MegaRoller LCC prototype tool are the total life cycle cost, discounted life cycle cost, and discounted cumulative cost as well as Levelized Cost of Energy (Table 5-3).

Table 5-3 Example of result indicators and related graphs.

Key indicators	Different figure types:
• *Total life cycle costs* - all the costs that will be incurred during the lifetime of the MegaRoller device. • *Total life cycle costs – discounted. Present Value of Costs PVC.* Present value of total life cycle costs is the estimated current value of a future amount to be received or paid out, discounted at the specified discount rate. • *Total CAPEX* - sum of all capital expenditures. CAPEX are incurred mostly at the beginning of a project. • *Total OPEX* – Sum of all Operational Expenditures. Expenses to run the business during the entire lifetime of the MegaRoller device -both non discounted and discounted values are calculated. OPEX may be broken down into sub headings such as annual O&M costs and sea bed lease rates. • *Levelized cost of energy LCOE* - LCOE of the MegaRoller device can be thought of as the average total cost of building, assembly and operating the MegaRoller device,	• *Total life cycle costs.* The figures visualize the ranking of different scenarios by total costs. Separate figures for discounted and not discounted costs. • *Cash flow.* The cash flow -figure is a report giving a general view of the distribution of cash flows for the calculation period. The figure is presenting both cumulative free cash flow and cumulative discounted free cash flow per measure. • *Cost categories.* The figures visualize the distribution of costs items behind the main cost category (i.e. CAPEX, OPEX)

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per unit of total electricity generated over an assumed lifetime.	

MegaRoller LCC supports design and investment decision-making, which means that calculations are performed before the costs are realised and the calculations are based on estimates of future values, which are inherently uncertain. If calculation parameters are highly uncertain it obviously leads to uncertain results which do not provide enough information for decision making.

Step 6 'Sensitivity analyses' Although point estimates are typically used in decision-making, it is also essential to analyse uncertainty related to the analysis results. Sensitivity analysis can be performed e.g., by Monte Carlo simulation which is useful especially when uncertainty of several calculation parameters needs to be considered at a same time. If uncertainty of only one or a few calculation parameters is considered, the simple what-if calculation can be conducted i.e. result values are re-calculated after the selected calculation parameter value is changed.

It should be noted that sensitivity analysis may lead to completely different results than results with original input values. One way to conduct the analysis is by identifying few input variables that probably affect the profitability the most. After this, the user can feed the most critical input variables into the calculation.

Step 6	Sensitivity analysis	Which assumptions need to be tested? What comes out if you change parameters? How sensitive are the results to changes in estimates and model features (assumptions)? What are the ranges of values of cost, discount rate, lifetime etc. that are appropriate for testing? How would you see the difference in decision criteria and indicators when using only optimistic and then only pessimistic estimates?

After completing the assessment, the results are ready to be put to practice. Results and recommendations can be reported in written form. In practice, quantitative measures should be used as a guide rather than as a sole basis for the decision.

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Appendix A: Acronyms and Abbreviations

List of Acronyms and abbreviations

AM	Adaptive Management
A&I	Assembly & Installation
CAPEX	Capital Expenditure
CBS	Cost Breakdown Structure
EIA	Environmental Impact Assessment
EMEC	European Marine Energy Centre
eLCC	Environmental LCC
FBD	Functional Block Diagrams
FCI	Failure Criticality Index
feLCC	Financial and Environmental LCC
fLCC	Financial LCC
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
FTA	Fault Tree Analysis
GWP	Global Warming Potential
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
MRE	Marine Renewable Energy
MTTFF	Mean Time to First Failure
OES	Ocean Energy Systems
OPEX	Operating Expense
OWSC	Oscillating Wave Surge Converters
O&M	Operation and Maintenance
PPA	Potential Problem Analysis
PTO	Power Take-Off
PVC	Present Value of Costs
RBD	Reliability Block Diagram
RCM	Reliability Centred Maintenance
RIA	Research and Innovation Actions
RPN	Risk Priority Number
SADT	Structured Analysis and Design Technique
sLCC	Societal LCC
TRL	Technology Readiness Level
WEC	Wave Energy Converter

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