RiaSoR2: Roadmap for Condition Based Monitoring and Reliability Centered Maintenance

Johannes Hüffmeier, and Pierre Ingmarsson

***Abstract*— Marine energy devices operate in a harsh environment but still need to perform reliably and produce the expected amount of energy, which give rise to huge engineering challenges. The Reliability in a Sea of Risk (RiaSoR) project addresses the strategic need for the marine energy industry to assess reliability that largely impact the Levelised Cost of Energy (LCoE) of emerging wave and tidal device technology. RiaSoR brings together three leading European research and testing sites from the north of Scotland, England and Sweden in order to develop industry approved reliability methodologies.**

The RiaSoR II project leverages technology and practices from the automotive industry, thereby going beyond the current state of the art in condition monitoring for offshore applications. By utilizing IoT principles for monitoring of sensor data and cloud-based service architectures for Big Data processing and analytics, the ocean energy sector will benefit from access to large volumes of data to improve reliability. A reliability centered maintenance guideline is established within the project.

The evolution of the Internet into an "Internet of Things" (IoT) whereby many connected devices with various sensors are continuously feeding real-time data into a remote data processing infrastructure, often referred to as a cloud is enabling many new concepts and business opportunities for remote operation and control of industrial applications, including condition monitoring, predictive and preventive maintenance. When the number of connected devices and sensors grow, sophisticated high-performance data processing services are required for the systems to be scalable to increasing data volumes. A plethora of protocols and standards exist for communication of sensor data between connected devices and cloud infrastructures, some of which will be used in the RiaSoR II project.

***Keywords*— Ocean Energy, Condition Monitoring Systems, Wave Energy Converters, Reliability, Availability, Maintainability, Reliability Centered Maintenance**

I. INTRODUCTION

DIGITALISATION and Internet of Things (IoT) allows for new approaches when it comes to operation and maintenance of assets. Within the Riasor2 project, RISE has established a roadmap for Condition Based Monitoring and Reliability Centered Maintenance towards

- an efficient integration of ocean energy in virtual power plants combining the advantageous of different intermittent power sources towards a reliable energy supply
- a smart operation and maintenance of the assets minimising the risk for outages, unplanned visits, smooth consumption of the lifetime of all components and maximum energy yield.

The era of digitalisation began almost half a century ago, but the societally major impacts of digitalisation are still to materialise. Recent advances have sped up the digital revolution by Internet of Things (IoT), data centres and cloud-based services. Digitalisation is fast becoming the inevitable solution to updating the industry (with 90% of data just created in the last two years), but particularly in three specific areas: **Connected designs** – where organisational efficiency leads to improved design performance and highly responsive and integrated supply chains. **Connected plants** – where operational efficiency and utilisation of assets, workers and associated processes are transformed to deliver a substantially higher level of productivity. **Connected customers** – where radical improvements in marketing, sales and support of product results mean dramatically improved customer experience, and in turn additional revenues. To gain access to its full potential in the ocean energy sector, new techniques are needed to optimise processes throughout the entire value chain and a clear roadmap based on the work in the **RiaSoR 2** project.

Paper ID 1323, track OMD (Operations, maintenance and decommissioning)

This work was performed within the OceanERANET project RiaSoR 2, co-funded by the Swedish Energy Agency and Highlands & Islands Enterprise.

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It is predicted that ocean energy could experience similar rates of rapid growth as the whole renewable energy market (40%), contributing significantly towards 300 GW installed capacity and generating more than 2000 TWh annual energy to the grid by 2050 in line with the Paris agreement and UN's sustainable development goals. Europe is at the forefront in developing ocean energy technologies and digital solutions for energy systems. Several developers are conducting large scale testing and demonstration to validate components, subsystems and materials for future commercial ocean energy arrays. However, there are three main challenges to address to for Europe to maintain as international leader and to reach market-readiness in a larger scale for employing farms/arrays at sea (OES and IEA): **Reliability, Performance and Cost Reduction** (towards 15 ct€/kWh in 2025 for tidal and 20 ct€/kWh in 2025 for wave energy as stated in the SET plan)**.** Digitalisation facilitates new possibilities (currently not available) that will cut across all three of these challenges, utilizing cutting edge artificial intelligence, cloud services, big data and advances in remote sensing to deliver a game changing approach to ocean energy to reduce the cost of key technologies. It is important to achieve knowledge increase that will deliver advanced analytics built up across the European supply chain to deliver vastly improved **Reliability**, increased levels of **Performance** that contribute to lower **LCoE** to a robustly enhanced ocean energy sector, shortening time-to-market, reducing risks for investors and opening business opportunities for new players.

There are some cornerstones in the roadmap needed to reach these ambitious targets, which are described in this paper.

II. Systematic Approach to Condition Based Monitoring

Ocean wave and tidal energy converters are regarded as one of the most promising marine renewable energy technologies. However, since marine energy devices operate in harsh environments but still need to perform with a high level of reliability to lower the levelized cost of energy (LCoE) to a competitive level there are significant technological challenges to overcome, including hardware dimensioning, fault-tolerance and maintenance strategies. At the same time, the certainty in prognoses of energy yields is higher than for many other renewable energies.

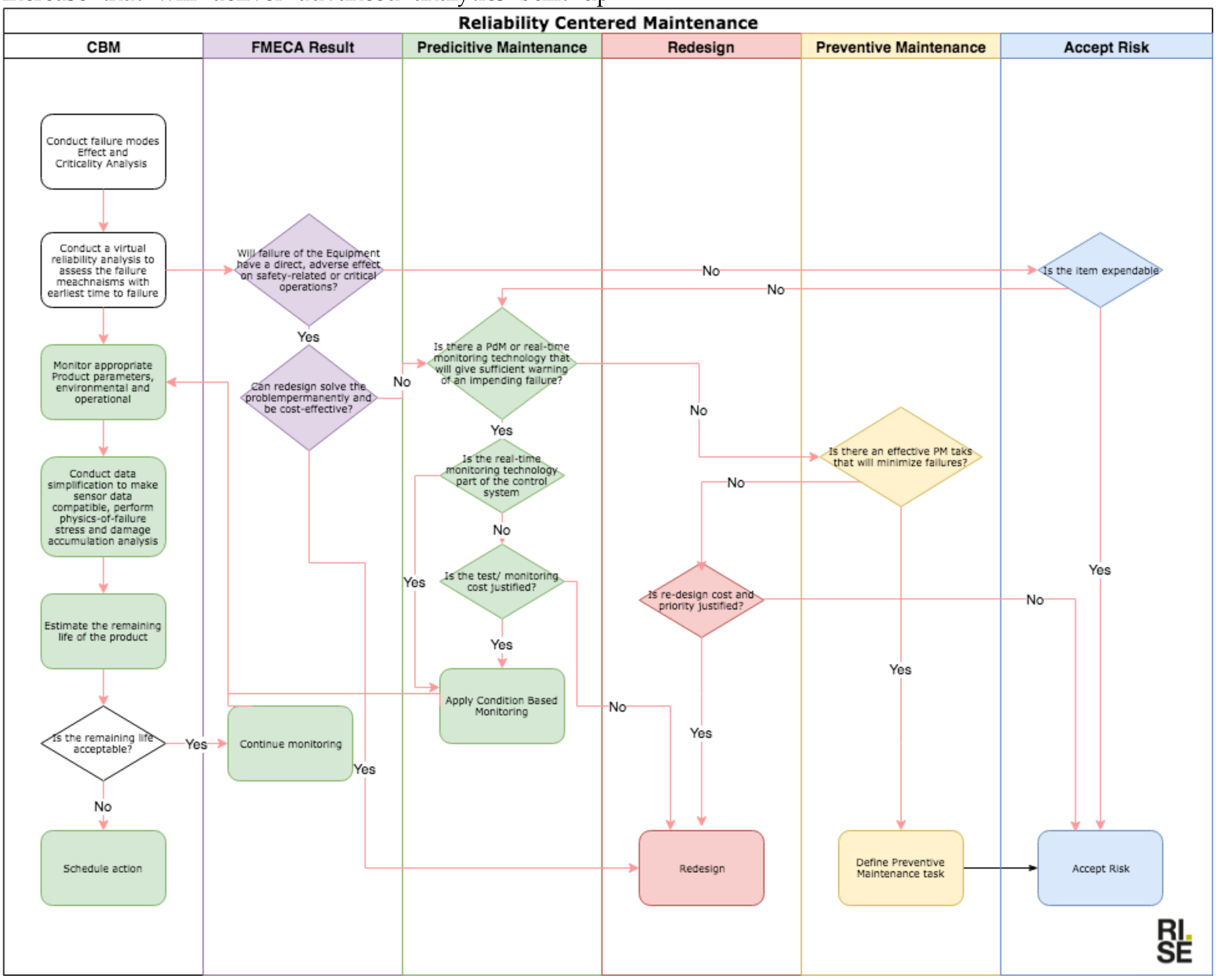

Fig. 1. Process chart for the RCM evaluation derived in the RiaSoR2 project.

Condition based monitoring and reliability centered maintenance requires decisions to be supported by sound technical and economic justification. The required approach needs to e.g. consider the consequence of failure of a given component. For example, an identical make and model of components can be used to support different operations. The consequence of failure and the maintenance approach of the two units are different, based on the system used. RCM analysis carefully considers the following questions:

1) What does the system or equipment do; what are its functions?
2) What functional failures are likely to occur?
3) What are the likely consequences of these functional failures?
4) What can be done to reduce the probability of the failure, identify the onset of failure, or reduce the consequences of the failure?

The goal of an RCM approach is to determine the most applicable cost-effective operation and maintenance technique to minimize the risk of impact and failure and to create a hazard-free working environment and maximize up-time while protecting and preserving capital investments and their capability.

The systematic approach to reliability centered maintenance are shown in the figure below.

With the objective to increase the reliability, availability and maintainability of ocean energy converters to reduce the time-to-market and enhance Europe's lead in ocean energy system development and deployment by introducing digital solutions for the ocean energy sector, structured approaches covering all parts of the WEC and TEC's systems and infrastructure need to be considered, strongly connected to the technical and economic justification.

Feasibility, experimental demonstration, validation of innovations, and performance assessment are complements to ensure that designs and approaches are based on facts. To facilitate common development of components and agreement on common interfaces will allow the whole industry forward and will need to be considered to allow for common learnings and to take advantages of scaling up production. These elements were used are need to define three roadmap objectives which will deliver against a number of the recommendations from the TPOcean Strategic Research Agenda (2016), specifically:

• Ensuring that best practice developed from experience is followed where possible to use the most appropriate materials, components and subsystems

• Ensuring that design considers FMECA -Failure Mode Effects and Criticality Analysis principles

• Ensuring that components and systems are tested to provide reliability data and inform system design

III. Reliability Centered Maintenance for Ocean Energy Devices

The goal of an RCM approach is to determine the most applicable cost-effective maintenance technique to minimize the risk of impact and failure and to ensure maximum uptime and create a hazard-free working environment while protecting and preserving capital investments and their capability.

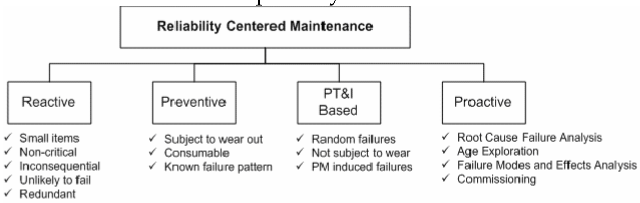

Fig. 2. Components of an RCM Program [1]

The various stages of development of OECs have different requirements for data acquisition. Understanding and analytics of the data is crucial to counteract faults that are detected and enhance production. The work performed within the 'RiaSoR2' portfolio on reliability methods, pre-conditions for failure mode detection, and system architecture can be applied to derive a condition-based monitoring system for OECs. Clear targets for the system, FMECA approaches, Reliability Availability Maintainability (RAM) based evaluations, detailed assessment of uncertainties through Variation Mode and Effect Analysis (VMEA), hybrid solutions for integration with the control system and for pre- and post-processing locations are concluded to be the most cost-efficient and effective solutions. As new components, materials and design solutions are used in all OECs and the effect of variable met-ocean conditions is uncertain, there is often a knowledge gap on failure modes. Design studies in the project will focus on user needs covering environments vital for the operation of ocean energy converters. This includes system design, decision support, operator interface design, signage, markings, technological support tools and new sensors. Important steps in the process are:

1) D**esign:** Clear technical requirement specification and KPI's that ensure cost-efficient and effective solutions derived throughout the project. This includes requirements on reliability of sensors and time span to detect failures in time.
2) **Prevention:** Significantly increased knowledge on failure modes of components and systems by accelerated testing and offshore testing, reducing the most probable sources of failure modes.
3) **Detection:** Quicker, more reliable and more robust sensor applications for failure detection, confirmation, localization and assessment on all types of OECs.
4) **Design:** Improved design for critical operations, reducing the potential for human error, accelerating

time for sensitive tasks and providing more comprehensive and effective decision support.

5) **Communication:** More flexible and efficient data handling and communication regardless of type of system or component.
6) **Enhancement:** Development of digital twin systems to enable faster and more reliable design solutions and rapid problem solving/ rapid prototyping.
7) **Improvement:** Ensure efficiency of the system by analysing collected data on failure modes, time-between failures, detection accuracy.
8) **Analysis:** Give evidence on load and stress estimations, uncertainty, tolerances and step-changes

IV. Smart Operation of Ocean Energy Devices for High Energy Yields Towards Virtual Power Plants

In this section a proof-of-concept (PoC) demonstrator is described and a use case focusing on fatigue of a critical WEC component is described.

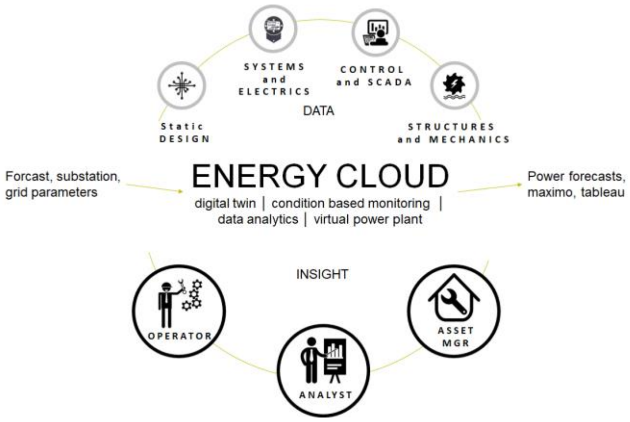

Fig. 3. The energy cloud as a base for smart operation of ocean energy devices towards a virtual power plant.

V. The Digital Twin

The performance of technical systems, the human-technical design interfaces and the manual operations together cover all the possibilities for strengthening the understanding of operations, diagnostics and structural health of ocean energy converters. *Digital Twins* are virtual representations of assets, used from early design through manufacturing and operation, maintained and easily accessible throughout a systems lifecycle. It is used for visualising monitoring data of systems and components, structure and represent data to operators, asset managers and analysts. Digital Twins have been known since 2002, but only gained momentum in 2017 when they became cost-effective thanks to an increase in the adoption of the Internet of Things (IoT) and cloud technologies, which enable low cost, high storage and computational capacity, high throughput messaging, security. This pairing of the physical and digital world makes it possible to analyse data and foster the visibility, predictive and preventive maintenance, and what-if analysis needed to understand the behaviour of the assets by creating scenarios that are difficult to replicate in real life. A Digital Twin is today a requirement for certification in the wind industry, secure efficient processes in the entire value chain covering – based on needs – the component level, sub-system, arrays and connecting infrastructure.

1) **Interface:** Facilitate a standardized platform for Digital Twins in the ocean energy sector fostering global research integration and cooperation.
2) **Analysis:** Provide evidence of working concepts of "smart" OECs based on a Digital Twin platform by testing in representative environment
3) **Analysis:** Replicate (real) measured events, with a sensor layout derived from the other WPs to achieve high accuracy.
4) **Design:** Analysis tool development and impact achieved by the Digital Twin in prototype testing, rapid prototyping, sensor data fusion.
5) **Efficiency:** Increased effectiveness based on the Digital Twin.

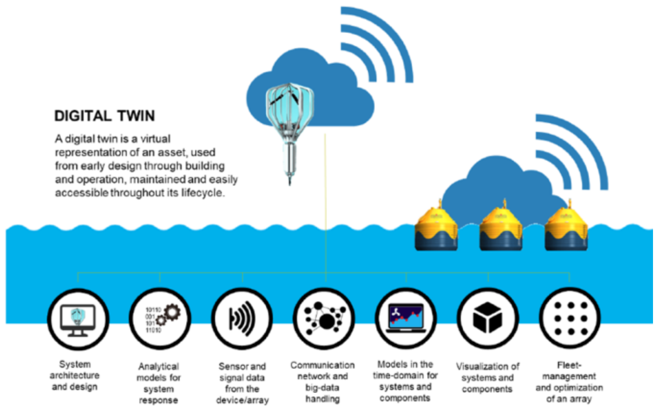

Fig. 4. Digital Twin as a base for efficient operation of ocean energy devices

VI. The standardized SCADA system

Supervisory Control and Data Acquisition (SCADA) is a data-gathering approach to provide real-time and historical information for supervision and remote and local control of individual or multiple assets. It is used by various industries such as wind and has established standards. In the development of wave and tidal energy converters, so far, no standardization has taken place that would allow for more unified connection and interaction between systems used for operation, control, monitoring and maintenance.

Provide systemised control of OEC farms and arrays through a unified SCADA system could improve energy yield and simplifies O&M. This could lower the LCoE by 15% and increase electricity production by 15% through real-time data collection, handling and analytics for predictive and preventive maintenance."

The SCADA interface needs to be the single interface to the OECs and all information and controls should be described in this one system, both locally and remote. Integrated condition monitoring functions, OEC and array control settings, and failure and alarm handling will all be included and configurable.

The following targets and goals need to be considered.

1) **Detection:** Distributed intelligence in components to enable reduced functionality in the event of errors.
2) **Communication:** Wider use of modular integrated communications systems in both capacity and function, designed to work together through open standards.
3) **Interface:** Web-enabled communication for all critical components in remote OECs and substation to facilitate remote state monitoring diagnostics.
4) **Response:** A "seamless and location-independent IT and communication network" from the operator's point of view.
5) **Efficiency:** Reduced LCoE/ increased electricity production.

VII. THE RIASOR2 PROJECT

Within this Riasor projects leading WEC/TEC developers are providing results from their onshore and offshore testing to identify critical components and parameters that influence uncertainties and safety factors. RiaSoR II is aimed at taking the RiaSoR I theoretical reliability assessment framework and applying it to the field test programme for WEC/TEC developers to validate the findings, establish a practical monitoring platform and guidelines to prepare for future arrays were big data handling and processing will be vital to drive down operational expenditures (OPEX). Through design iterations, the design was improved in terms of reliability and then a final reduced set of sensors was deployed in the commercial assets. The progress beyond state of the art was to apply the guidelines with inspiration from the automotive industry to the off-shore wave energy industry. The RiaSoR2 project has established a roadmap for smart operation of ocean energy devices. The project itself has put a basis for the roadmap by the following benefits:

- Requirements analysis regarding data capture, processing and communication for Condition Monitoring of WECs
- RiaSoR 2 methodology fully utilized in planned test programs for technology developers
- Based on offshore wind energy industry best practice in condition monitoring systems, the training and material developed will help transfer skills in reliability analysis and use of the monitoring framework to WEC and TEC developers
- The educational material that help wave and tidal energy developers adopt an informed approach to condition monitoring and also make a significant and lasting impact
- Structured, FMECA based approach for condition-based monitoring for ocean energy devices
- Use case to exemplify based on data from dry and offshore testing
- State of the art in capturing failure modes by sensor techniques
- Adoption of data capturing and processing from other industries
- Numerical modelling for capturing and quantifying the uncertainties in reliability assessment
- RiaSoR roadmap for CBM of ocean energy devices
- Dissemination at various conferences on content to spread results and receive feedback
- Interaction with other parallel projects (Waveboost, etc.)

Achievements of the project include:

- Overview of condition monitoring system requirements for wave energy converters to include sensor technology selection, data processing and communication.
- Protoype implementation of WEC condition monitoring system
- Completion of condition monitoring educational and training package.
- Delivery of workshop on the training package to ensure guidelines are understood and welcomed by industry.
- System architecture for data handling and data communication
- VMEA study for critical parts and for CBM
- Data assessment, tolerances, data quality and handling of outliers
- Structural health, remaining lifetime, safety factors and uncertainties

VIII. CONCLUSION

The new technologies offer immense potential for new products and services and provide new possibilities for solving problems and fulfilling product functions including cloud-based services detecting failures on wind turbines months in advance. The numerous new technologies applied (Internet of Things, Big Data) together with Virtual Reality, Augmented Reality and more, offer opportunities to radically renew the business model. The RiaSoR projects roadmap works with starting points in research and innovation, reliability methods and testing that will impact the entire value chain (see figure 4). The roadmap triggers project to develop methods for reducing technological risks, O&M costs, ultimately lowering the cost of energy (LCoE). By covering all aspects about operations, maintenance and marine safety (HSE), the application of the roadmap will contribute to an efficient and sustainable Ocean Energy sector in Europe.

The roadmap will accelerate sustainable development of both OECs and the energy production of arrays by developing **increased digitalization enabling greater autonomy of process controls**. The CBM and Digital Twin will impact four areas that strongly affect the outcome of deployments of ocean energy arrays: **arrays, device, O&M and risks**. Each area/level will integrate and impact the value chain in different ways to lower the overall cost and increase the safety that will lead to increased possibilities of private investments.

On Device level: *Strengthen the collaboration in the entire value chain were suppliers are more integrated in the R&D process and future optimisation that will lead to improved performance of manufacturing processes and system operation. Increased efficiency of the system and reduced operational costs of ocean energy technologies is achieved by common interfaces and cross-company platforms for R&I.*

Provide a holistic SCADA and Digital Twin model for assessing the internal and external impact during operations of WEC's and TEC's. The digital solutions will then accelerate the learning curve for all stakeholders and visualise the needs for component development and will be able to use for park planning as well as to assist authorities in the decision process.

On Array level: The *RiaSoR roadmap will impact on decision and knowledge on certification and to plan the ocean energy renewable in the European energy mix. The digital twin will allow for optimised energy yield and impact the development of common rules and regulations on member state level.*

Pave the way for new technical and operational solutions by demonstrating their enhanced reliability impact and prepare guidelines for technical and regulatory implementation.

On O&M level: *Detecting faults in time is crucial for O&M planning. To integrate the supply chain via the digital twin will speed up common methodologies and lower the cost for future operations.*

Reveal additional reliability features with focus on human impact, including needs of training and understanding of human behaviour. The transfer of knowledge across the sector will contribute to new innovations and accelerate development processes for ocean energy O&M.

On Risk level: *To communicate lower risk, both safety and technology, to the market (costumers, investors) will impact the possibilities for future deployments of ocean energy arrays and integration of ocean energy renewables in the virtual power plant mix.*

The SCADA and Digital Twin open architecture together with physical tests will act as demonstration facilities with the aim to get investment security in early stages. The project will develop methods for reducing technological risks, O&M costs, ultimately lowering the cost of energy (LCoE). By covering all aspects about

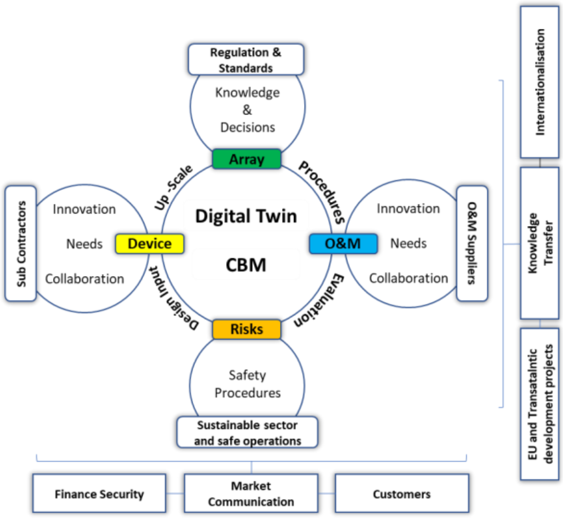

Fig. 5. Impact of RiaSoR roadmap throughout the value chain.

operations, maintenance and marine safety (HSE), the project will contribute to an efficient and sustainable Ocean Energy sector in Europe. Integrate the experience and knowledge from other industries (e.g. automotive, onshore wind energy), of utilities, operators and technology developers, and establish an international group of stakeholders to give relevant input to the further development in Europe.

Acknowledgement

This work was performed within the RiaSoR 2 project, -founded within the OceanERANET framework by the Swedish Energy Agency and Highlands&Islands Enterprise as well as in-kind efforts by the contributing companies. The valuable discussions and contributions by the project team consisting of Corpower Ocean, Waves4Power, Ocean Harvesting, ORE Catapult, EMEC, Alkit Communications, Synective Labs and RISE is deeply acknowledged.

Definitions and Glossary

Condition Based Monitoring is the acquisition and processing of information and data that indicate the state of an item over time

NOTE The item state deteriorates if faults or failures occur. [2]

Reliability/ Availability defined as the probability of a system or system component performing its intended function under stated conditions without failure for a given period of time. A precise definition must include a detailed description of the function, the environment, the time scale, and what constitutes a failure. [3]

The metric used to measure reliability/availability may be either:

§ Days operational/Days installed – although this will be skewed by days not operational in low power seas for extended maintenance. This equation does not take into account that a large proportion of energy will come during winter months, which may have been captured by the WEC.

§ ΣPower captured/ΣPower at site (where the 'Power at site' is related to the maximum possible energy which can be captured by the installed devices). This would acknowledge that power may be captured in high energy seas, and that extended summer maintenance may have little effect on overall energy captured for the year.

Reliability is the ability to perform as required, without failure, for a given time interval, under given conditions

NOTE 1 The time interval duration might be expressed in units appropriate to the item concerned, e.g. calendar time, operating cycles, distance run.

NOTE 2 Given conditions include aspects that affect reliability, such as mode of operation, stress levels, environmental conditions and maintenance.

NOTE 3 Reliability may be quantified using appropriate measures. [4]

Availability - ability to be in a state to perform as required

NOTE Availability depends upon the combined characteristics of the reliability, recoverability, and maintainability of the item, and the maintenance to support performance. [4]

Maintainability - ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance

NOTE Given conditions include aspects that affect maintainability, such as location of maintenance, accessibility, maintenance procedures and maintenance resources. [4]

Failure - A failure is the termination of the ability of an item to perform a required function

NOTE 1 Failure is an event as distinguished from fault, which is a state.

NOTE 2 Failure is the manifestation of a fault.

NOTE 3 A complete failure of the main capability of a machine is a catastrophic failure (as defined by the end user). [2]

FMECA - FMECA is a methodical process that provides identification of all the probable ways that parts, assemblies, and the system may fail, the causes for each failure, and the effect that the failure will have on the capability for the system to perform its mission is essential in the system design process.

Energy Yield - The net energy yield refers to the amount of energy that is gained from harvesting an energy source. This yield is the total amount of energy gained from harvesting the source after deducting the amount of energy that was spent to harvest it.

Virtual Power Plant - A virtual power plant (VPP) is a cloud-based distributed power plant that aggregates the capacities of heterogeneous Distributed Energy Resources (DERs) for the purposes of enhancing power generation, as well as trading or selling power on the electricity market.

Reliability Centered Maintenance - Reliability-Centered Maintenance (RCM) is the process of determining the most effective maintenance approach. The RCM philosophy employs Preventive Maintenance (PM), Predictive Maintenance (PdM), Real-time Monitoring (RTM1), Run-to-Failure (RTF- also called reactive maintenance) and Proactive Maintenance techniques in an integrated manner. These principal maintenance strategies, rather than being applied independently, are optimally integrated to take advantage of their respective strengths, and maximize device and equipment reliability while minimizing life-cycle costs. The goal of the philosophy is to provide the stated function of the facility, with the required reliability and availability at the lowest cost for the design lifetime. RCM requires that maintenance decisions be based on maintenance requirements supported by sound technical and economic justification.

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