MONITOR

Multi-model investigation of tidal energy converter reliability

Fostering renewable energies and energy efficiency

WP3 – Capitalization of Previous Project Outputs

Review of Prior Work

Revision

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Abbreviations

Abbreviation	Definition
AA	ATLANTIC AREA
ADV	ACOUSTIC DOPPLER VELOCIMETER
ALT	ACCELERATED LIFE TESTING
BEMT	BLADE ELEMENT MOMENTUM THEORY
CMS	CONDITION MONITORING SYSTEM
DfR	DESIGN FOR RELIABILITY
DFMEA	DESIGN FAILURE MODES AND EFFECTS ANALYSIS
DLC	DESIGN LOAD CASES
DOE	DESIGN OF EXPERIMENTS
DTOCean	DESIGN TOOLS FOR OCEAN ENERGY ARRAYS (project)
DVP	DESIGN VERIFICATION PLAN
EWTEC	EUROPEAN WAVE AND TIDAL ENERGY CONFERENCE
FEA	FINITE ELEMENT ANALYSIS
FMEA	FAILURE MODES AND EFFECTS ANALYSIS

Abbreviation	Definition
FMECA	FAILURE MODES AND EFFECTS AND CRITICALITY ANALYSIS
FBD	FUNCTIONAL BLOCK DIAGRAM
FRACAS	FAILURE REPORTING, ANALYSIS AND CORRECTIVE ACTION SYSTEM
FTA	FAULT TREE ANALYSIS
FTEC	FLOATING TIDAL ENERGY CONVERTERS
HALT	HIGHLY ACCELERATED LIFE TESTING
HASS	HIGHLY ACCELERATED STRESS SCREENING
HATT	HORIZONTAL AXIS TIDAL TURBINE
IDCORE	INDUSTRIAL DOCTORAL CENTRE FOR OFFSHORE RENEWABLE ENERGY
IEC	INTERNATIONAL ELECTROTECHNICAL COMMISSION
IMU	INERTIAL MEASUREMENT UNIT
LCOE	LEVELIZED COST OF ENERGY
MEC	MARINE ENERGY CONVERTERS
MTTF	MEAN TIME TO FAILURE
OPEX	OPERATING EXPENSE
O&M	OPERATIONS AND MAINTENANCE
PFMEA	PROCESS FAILURE MODES AND EFFECTS ANALYSIS
PLP	POWER LAW PROCESS
PoF	PHYSICS OF FAILURE
PTO	POWER TAKE OFF
QFD	QUALITY FUNCTION DEPLOYMENT
RBD	RELIABILITY BLOCK DIAGRAM
RBDO	RELIABILITY-BASED DESIGN OPTIMISATION
RBM	RIGID BODY MODEL
RCA	ROUTE CAUSE ANALYSIS

Abbreviation	Definition
RiaSoR	RELIABILITY IN A SEA OF RISK (project)
RUL	REMAINING USEFUL LIFE
SAT	SEA ACCEPTANCE TESTS
SME	SUSTAINABLE MARINE ENERGY
TEC	TIDAL ENERGY CONVERTER
TIPTORS	TIDAL POWER TAKE-OFF RELIABILITY SIMULATION (project)
UKCMER	UK CENTRE FOR MARINE ENERGY RESEARCH
VMEA	VARIATION MODES AND EFFECTS ANALYSIS
VPM	VORTEX PARTICLE METHOD
WEC	WAVE ENERGY CONVERTERS

1 Project Overview

The MONITOR project, funded by the Interreg Atlantic Area programme, is investigating the reliability of tidal energy converters (TECs), and will work with industry to develop tools to improve device reliability. The project aims to help increase the transition to renewable energy within the Atlantic Area (AA) by reducing device cost and improving reliability (see Figure 1 [1]). Monitoring systems will be developed which can be applied to any TEC, de-risking development and hence encouraging investment.

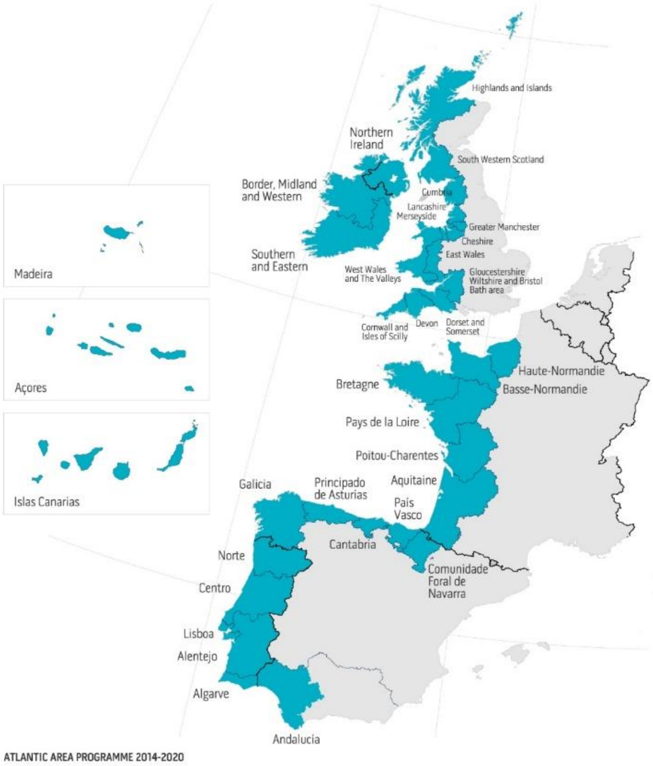

Figure 1: Atlantic Area Regions

The key objectives are [2]:

- Reliability: Provide tools and shared learning to developers to improve and optimise reliability of TEC
- Feasibility: Reduce risk in TEC, thus demonstrating feasibility to investors and public bodies;
- Development: Minimise the time to market in the development phase;
- Cost: Lower the cost of TEC development;
- Performance: Contribute to low operating expense (OPEX) and increased performance in the production phase;
- Growth: Develop the tidal energy industry and help foster growth of renewable energy sector.

The project will use Variation Mode and Effects Analysis (VMEA) to model the critical design and load factors influencing device reliability, with a focus on blades and support structures. Results of scale tank tests and at-sea testing on Sabella and Magallanes turbines will be used to refine VMEA models, and to validate a vortex particle method (VPM) code – DorothyVPM, and a blade element momentum theory (BEMT) numerical model - SwanBEMT. TEC developers are invited to engage with the project through workshops and forums, the first of which was held in June 2018, with subsequent workshops scheduled to take place at EWTEC 2019, and later in the project.

2 Document Aims and Scope

This document forms deliverable WP3-A1, the first deliverable of work package 3 (WP3), Capitalization.

Several previous projects - such as Reliability in a Sea of Risk (RiaSoR) – have developed reliability tools for aspects of TECs using VMEA. To avoid duplication and build on previous work a review of key outputs from previous projects related to TEC reliability has been carried out. This report summarises the reviewed work and highlights any gaps in knowledge and understanding.

Section 3 includes a brief overview of VMEA and its uses.

Section 4 summarises the scope and main outputs of several projects focused on TEC reliability and the use of VMEA in this context.

Section 5 discusses the scope and findings of wider literature focused on assessing and improving the reliability of tidal devices.

Section 6 summarises the key findings and next steps.

3 Introduction to VMEA

With a global ocean energy market forecasted to be worth £76 billion by 2050 [3], the prospects for marine energy capture device developers are tantalising. One such type of device is the horizontal axis tidal stream turbine, which harnesses the kinetic energy within the accelerated flow of water around coastlines to produce electricity. This technology is currently at the commercialisation stage, with various tidal stream turbine developers operating their devices and importing electricity into the local grid.

With any form of new technology, an essential performance characteristic to aid in the effective development and implementation of the technology into the commercial market is the reliability of the device. Increasing reliability is essential in producing a technology which can perform as required, whilst attracting investment for further development.

The MONITOR project aims to assess and predict the lifetime of tidal turbine blades and substructures through performing a VMEA for these individual components. VMEA is a method by which the reliability of each part of a design is analysed in turn to provide a quantified result indicating the reliability and uncertainty of the part in question. This allows for risks to be assessed and a design to be optimised to provide a more cost effective and reliable solution [4]. VMEA will help to de-risk the uncertainty of structural failures for tidal energy devices, ultimately helping to lower the levelized cost of energy for the devices and for the sector.

3.1 What is VMEA?

When designing a mechanical system or component, it is important for an engineer to be able to predict the life of the system or component to ensure the product is reliable and suitable for the application it is designed for [5]. Understanding the failure mechanisms which can contribute to or lead to the failure of the product helps in identifying weak parts/areas, which allows focus to be placed on improvement in these areas. However, with the traditional and more common Failure Modes Effects Analysis (FMEA) method, no measure is given of the reliability improvement when a weak part is strengthened.

The VMEA method was introduced to overcome this problem by providing a measure of uncertainties associated with the lifetime prediction of the product, introduced by unwanted variations in the lifetime prediction process [6]. FMEA studies have indicated that in the majority of cases, failure modes of engineered products are introduced by unwanted variations. VMEA gives a statistical measure of the reliability of the product by taking into account these unwanted variations. From this measure of reliability, well informed safety factors can be applied to the product.

VMEA works by considering the sources of variability in performing performance predictions to provide an uncertainty measurement in the final performance prediction. When applied to lifetime predictions, VMEA considers the uncertainty and variability in the parameters which contribute towards the final prediction of the life of the product. Many of the project outputs referenced in section 4 provide more details on VMEA, and so this won't be repeated here.

VMEA is commonly used in the automotive industry, and case studies of application of VMEA in other industries are another useful reference [7]. A considerable challenge in applying VMEA to tidal devices is that due to the relative immaturity of the marine renewables sector, the same vast quantities of historical data which can be utilised by other industries do not exist. As such methods of applying VMEA with limited statistical data need to be developed.

4 Prior Related Projects

This section of the report covers several projects and publications which considered TEC (or wave energy converter (WEC)) reliability, and approached this problem using a VMEA approach.

4.1 Reliability in a Sea of Risk (RiaSoR)

The RiaSoR project is in its second phase. RaiSoR developed and proposed a theoretical reliability assessment framework for marine energy converters (MEC), with guidelines based on existing practices from automotive industry. RiaSoR II began in September 2017 and is applying the theoretical reliability assessment guidelines developed in RiaSoR I to WEC in the field. WEC test devices have been selected for monitoring using several sensors. The data gathered has informed reliability assessment and been used to develop the assessment methodologies further. The project is now drawing to a close and will have a final workshop at EWTEC in September 2019.

Historical project outputs are summarized in Table 1 in chronological order, and can all be downloaded from the RiaSoR project website publications page [8].

Table 1: RiaSoR Project Outputs

Published	Deliverable Title	Description
04-2016	Review of standards on reliability for ocean energy and relation to VMEA [9]	Report summarizing existing standards (EMEC, ISO, IEC, CEN, DNV GL) which could potentially feed in to the development of guidance for performing VMEA.
12-2016	Reliability Guidance for Marine Energy Converters [10]	A comprehensive report from RiaSoR I, describing VMEA theory, reliability design for MEC, and the application of VMEA at different stages (concept, design, detailed design). Structural analysis, electrical systems and moorings and foundations are given specific focus.

Published	Deliverable Title	Description
12-2016	VMEA: Short Reference Guide	This is a separate document only containing Appendix A of Reliability Guidance for Marine Energy Converters and provides a concise summary of VMEA.
12-2016	Moorings and Foundations Catalogue, Deliverable 5.1 [11]	Table containing details of mooring and foundation types, and their applicability to different seabed types and depths. Strengths and weakness and common failure modes are also noted. The document is focused on wave devices but is relevant to TECs also.
12-2016	Industry Workshop Day 1: Developing an Understanding of the VMEA Framework [12]	First slide pack from a two-day workshop, with introduction to the VMEA framework and several worked examples.
12-2016	Industry Workshop Day 2: The VMEA Framework in Practice [13]	Second slide pack from a two-day workshop, with RiaSoR case studies on Pelamis moorings (basic to probabilistic VMEA), and WEC piston rod strength (basic VMEA and enhanced VMEA).
12-2016	VMEA Spreadsheet Template [14]	An excel document to allow the user to input strength and load uncertainty components, along with values for scatter and uncertainty, sensitivity, correction and standard deviation. The sheet then calculates the safety factor and any required additional factor.
02-2018	RiaSoR II Condition Monitoring Requirements and Needs [15]	A report on the requirements for data capture and processing for a condition monitoring system for WEC. Includes requirements of the data capture system, communications, processing, and interfaces.
05-2018	Outline Load Assessment Numerical Tool [16]	A report describing the development of a generic WEC model in MATLAB/Simulink to estimate loading, and a proposed approach for reliability assessment of these loads. An overview of VMEA and condition monitoring systems (CMS) is also given. The model includes hydrodynamics, body properties, constraints, power take-off, and mooring. The reliability approach proposes the intended methods of applying VMEA to WEC with use of the model.
06-2018	Condition Monitoring Systems of Wave Energy Converters [17]	A report focused on the sensors and data acquisition of the CMS, giving an example architecture for a WEC device. The appendix also details commercially available CMS.
06-2018	RiaSoR II Training Requirements [18]	A report which describes the requirements of a user training package for use of the WEC CMS.
12-2018	Reliability Evaluation of CorPower Pre-tension	This report utilizes the reliability and data processing methodologies to evaluate the structural reliability of components in a WEC. VMEA reliability assessment of a

Published	Deliverable Title	Description
	Cylinder using VMEA [19]	pre-tension cylinder is compared to design calculations based on pressure vessel standards.

There are many useful points in the above documentation, too much to present all of it in this report, however some key observations are detailed below.

- A comprehensive review of VMEA theory and case studies has already been compiled and is a useful reference for MONITOR.
- In general, the RiaSoR and RiaSoR II reports will provide a useful basis for working through refining the VMEA for the TEC devices considered in MONITOR.
- Gathering sufficient knowledge and data is key with regards to being able to reduce safety factors.
- In a structural case study of a WEC component, the largest contributor to uncertainty was assumed variation from site to site – recommendations are to measure at many locations and improve accuracy of this estimate, or to have an adaptable design.
- The second largest contribution to errors was the hydrodynamic model. In-service measurements to calibrate the model would be useful.
- Strength scatter will be an unavoidable source of uncertainty. Ideally this should dominate when other sources have all been reduced by analysis refinement.
- The accuracy of all of the below needs to be increased in order to lower safety factors:
    - Load estimations (e.g. wave, tide, turbulent loads)
    - Hydrodynamic Modelling
    - FE models
    - Fatigue models and material understanding
- Even within this project there appear to have been different spreadsheets and templates used for assessment of different systems. A clean way of integrating/standardising these seems to be a point which should be focused on, although perhaps is a long-term goal. Difficulties arise because devices differ and levels of data available differ significantly from project to project, though in future the available data could be standardized as standards and guidance become more commonplace.

The RiaSoR projects have focused more on WEC than TEC, and as a result have not applied the VMEA process to blades, or to the types of substructures being considered in MONITOR. However, they have provided a strong framework and examples of applying this to MEC devices and their components and will be a useful reference throughout the project.

There are other published documents which refer to VMEA of WEC devices and components, some of which the authors were involved in the RiaSoR project consortium, but the outputs are not evidently specifically linked to the project. For example, a large slide pack [20] was found which covers aspects of fatigue testing, modelling and design. This includes covering the statistical methods which form the basis of the VMEA methodology for reliability assessment and then case studies including for the piston rod for a point absorber WEC. The VMEA takes the calculated expected life, then assigns a common uncertainty metric to each individual error and variation source, then calculates an overall uncertainty for life which is used for determination of a proper safety factor.

4.2 Tidal Power Take-Off Reliability Simulation (TiPTORS)

The Tidal Power Take-Off Reliability Simulation (TiPTORS) programme has been run in multiple stages with different project partners.

4.2.1 TIPTORS Phase 1

Phase 1 of the project ran in 2015 and was a collaboration between ORE Catapult and Ricardo UK and the objective was to develop and validate a Design for Reliability (DfR) methodology targeted specifically at tidal stream power take-off devices, using best practice approaches from other industries to help reduce risk at the design and testing stages.

The publicly available outputs of this project are listed in Table 2.

Table 2: TiPTORS Phase 1 Project Outputs

Published	Deliverable Title	Description
Sep 2015	Design for Reliability Methodology - Summary Report [21]	This report summarises TIPTORS Phase 1 development of a DfR methodology, focused on horizontal axis tidal turbines (HATT). A flowchart is provided which shows a total of 16 DfR processes integrated into the various stages of a generic design process, e.g: • Failure Modes and Effects and Criticality Analysis (FMECA) • Reliability Block Diagram (RBD) • Root Cause Analysis (RCA) • Fault Tree Analysis (FTA) • Failure Reporting, Analysis and Corrective Action System (FRACAS) These are categorized as essential, recommended or optional, and scored with regards to cost, resource and complexity. This table is in Appendix 1: Table of DfR Processes from TIPTORS. Each of the processes is described in the document in terms of objective, key steps, deliverables, and a checklist for the reader when implementing the process. This is a useful reference point for reviewing existing processes and when best to use them.
Sep 2015	Design for Reliability Tool – Specification [22]	This second report from the TiPTORS project proposes methods for development of a power train reliability simulation tool.

This work was also presented at several conferences by ORE Catapult during the project.

There are also several other documents which were created as part of the project. These documents are described in Table 3. The documents are stored on ORE Catapult's server and may be available on request if required.

Table 3: TiPTORS Phase 1 Reports - Not Publicly Available

Published	Output Title	Description
Jan 2015	Engineering design for reliability processes applicable to tidal turbines	Report which includes details of DfR tools and processes which could be applied to tidal energy. Information is taken from other more mature industries.
Mar 2015	General Industry Practice and Design Parameters	Report which discusses HATT configurations and operational methods which will affect reliability. Describes design and operating considerations
Mar 2015	Quality function deployment	Report which details the Quality Function Deployment (QFD) process. The process helps to translate customer requirements into technical requirements.
Mar 2015	Definition of System Architecture of Horizontal Axis Tidal Turbine (HATT)	This document presents an enhanced functional block diagram (FBD) for tidal turbines. Describing the device in this way can allow for the system architecture to be used in other DfR processes.
Mar 2015	Initial reliability block diagram algebraic structure	Report which describes how to construct an RBD, either at a system or component level, and how this can be used to calculate system reliability. The difference between series and parallel systems, and between active and standby redundancy is also covered.
Mar 2015	Reliability allocation process for horizontal axis tidal turbines	Report which describes the process of allocating target reliabilities for systems and components. The report recommends using weighted reliability processes, using surrogate data from the wind industry, and developing failure rate predictions for HATT subsystems.
Mar 2015	Change Point Analysis Process	Report which details the process of Change Point Analysis (CPA). This process is used during development of a device, where design iterations are occurring. It is a tool to help understand how much the design has changed from earlier versions and evaluate the associated risk. These risks should then feed into an FMEA or other as appropriate. Changes to process are also included.
undated	Reliability Tool Diagram	1-page diagram showing where aspects of a reliability modelling tool would fit in the design process.
Mar 2015	FMECA Guide Tool for Tidal Turbines	Report which describes FMECA for systematic analysis of potential failure modes. A bottom up/component approach is recommended as being better suited to assessment of performance and reliability at a component level than top down/functional approach.
Apr 2015	Testing requirements for tidal turbines	Report which describes how to check the robustness of a design verification plan (DVP) developed as part of a FMECA, including noise factors. Noise factors tend to be parameters which cannot be controlled and should be incorporated into the test plan.
Apr 2015	Physics of Failure & Condition Monitoring Processes	Report which considers how best to understand the specific failures which occur within TECs. The “bathtub curve” is used to represent failures. Wind turbine sensor equipment

Published	Output Title	Description
		is reviewed for suitability to TECs and to Physics of Failure (PoF) techniques.
May 2015	Failure reporting, analysis and corrective action system (FRACAS)	This report describes FRACAS, a system which can be used to log and analyse failures to determine root causes and propose corrective actions. Every failure will be documented, investigated, and action taken. This process is particularly important during development and testing, where there is scope for design changes and corrective action.
Jun 2015	Design of Experiments	This report provides a high-level overview of Design of Experiments (DoE) and its potential uses to help increase TEC reliability. A worked case study is used to explain the main concepts.
Jun 2015	Root cause analysis methodology	This report describes RCA as part of FRACAS in more detail. Guidance is given for anyone carrying out RCA, as well as some common techniques which can be used.
Jun 2015	PFMEA and control plan guide tool for tidal turbines	This report covers the use of Process Failure Modes and Effects Analysis (PFMEA) and Control Plans to manage manufacture and assembly of components. The control of these processes will influence the reliability of the finished components and systems.
Jun 2015	Life data analysis & system reliability analysis	This report describes the Life Data Analysis processes at a basic level. These processes can be used to predict product lifetimes based on small samples, but knowledge of statistical methods is required to implement these processes. System Reliability analysis is also described, which aims to represent the time to failure of a full system based on each of the components and subassemblies. Analysis of the influence of off-the-shelf components on full system reliability in addition to bespoke components is recommended.
Jun 2015	Fault Tree Analysis	This report contains guidance on using FTA, to identify (and avoid) potential causes of failures, or to carry out root cause investigation. It differs from FMEA by considering parts and subsystems in relation to each other. It can be a costly and time-consuming process but useful to visualise and understand full systems.
Jun 2015	Reliability Growth and reliability demonstration testing	This report provides guidance on the Reliability Growth and Reliability Demonstration Testing processes. Reliability Growth programmes test and improve devices (usually either design or manufacture), monitoring the positive change in reliability over time. Reliability Demonstration Testing does not necessarily seek to improve reliability, but to prove that a system has met requirements – this is usually done when a contractual requirement.

Published	Output Title	Description
Jun 2015	Highly accelerated life test (HALT), highly accelerated stress screen (HASS) & accelerated life test (ALT)	This report introduces the test philosophies HALT, HASS and ALT, which aim to find and correct weaknesses in components and systems at an early stage. HALT determines the operational and destruction limits of a design and aims to improve these weaknesses. HASS is more of a verification method, applying stresses within those expected in usage (albeit at the high end of the scale). ALT aims to excite a specific failure mechanism and accelerate the occurrence of this. Extensive knowledge seems to be needed to properly define and execute these tests.

4.2.1.1 Observations from TiPTORS Phase 1

A large amount of work has been done to identify and introduce many different DfR tools, although many of these are not covered in detail within the above reports and the requirement for additional knowledge and use of reference material is highlighted.

The project focused on PTO, rather than blades and substructures, however limited TEC data sets were available in the project (it appears this was partly due to delays in signing NDAs), and so the outputs of the project are still fairly generic. It is also noted that the DfR methodology had not been mapped to specific developers design processes.

It is noted in the produced documentation that there are knowledge gaps with regards to failure mechanisms and 'physics of failure' – component testing could fill these potentially. Additionally, improvement of data collection is recommended.

It would be useful to work through each of the DfR processes in detail and apply/adapt these to TEC blades and structures. A lack of basic legacy data makes adopting DfR methodology difficult. Estimates should be made in early reliability modelling, with the accuracy increased when data becomes available (as planned in MONITOR).

4.2.2 TIPTORS Phase 2 – Reliable Simulation for Tidal Power Take Off

Phase 2 of the project, Reliable Simulation for Tidal Power Take Off (PTO) was undertaken by a student, Fraser Ewing, at the Industrial Doctorate Centre for Offshore Renewable Energies (IDCORE) in conjunction with DNV GL and University of Strathclyde.

The aim of phase 2 was to develop a simulation tool, using relevant parts of the Design for Reliability methodology, that could be used to evaluate the reliability of tidal stream power take-offs and ensure design-life is met, as well as promote improved designs and innovation to reduce the cost of energy. The initial aim was to aid technology developers to deliver successful first tidal arrays; a further aim was to develop a component Reliability Database, to be used to drive the Simulation tool and as a data source for the industry.

The outputs by Fraser Ewing which appear to be linked to this project are listed in Table 4. The project has also been referred to as Tidal Turbine Digital Twin.

It should be noted that it is not clear whether all of the below outputs can be linked back to TiPTORS Phase 1, or whether this list is exhaustive, although it contains all of the sources which could be found.

Table 4: TiPTORS Phase 2 – Reliable Simulation for Tidal Power Take-Off Project Outputs

Published	Deliverable Title	Description
Sep 2016	Development of a Tidal Stream Turbine Reliability Prediction Tool [23]	This conference paper was included in the Conference for Offshore Renewable Energy (CORE), 2016. The paper proposes a simulation tool for improved reliability prediction, using surrogate reliability data and a system engineering model of the TEC power train. Bayesian methods are used to combine the above, and the probability of failure is then generated. Nominal, off-design and faulty conditions were looked at.
Jan 2017	A Bayesian Updating Framework for Simulating Marine Energy Converter Drive Train Reliability [24]	Conference paper, included in the 5th annual Marine Energy Technology Symposium, 2017. The paper highlights that MEC reliability assessment is generally carried out with surrogate data and carries unquantified uncertainty levels. A Bayesian framework has been developed for drive train components using onshore wind data, with the aim of later updating it with MEC field data. Bayesian updating statistical methods aim to define uncertainty of parameters of a statistical model. It can predict future performance with little data, and with disparate data sources.
Jun 2017	Reliability Prediction for Offshore Renewable Energy: Data Driven Insights [25]	Conference Paper included in ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. This paper tests two aspects of reliability assessment. The constant failure rate assumption, and the non-Homogeneous Poisson Power Law Process (PLP) model which is used in onshore wind reliability assessment. It is asserted that pitch systems and generators should not be assumed to have constant failure rates if performing a reliability assessment using non-repairable surrogate data. For repairable systems the PLP model is not always accurate. In general, the paper reviews different assumptions and statistical methods used in reliability assessment and the validity of these to drive train components. The work is particularly relevant if using onshore wind data as surrogate for a MEC assessment.
2018	Development of a Digital Twin for Tidal Turbines [26]	This poster was presented as an update at the SuperGen UK Centre for Marine Energy Research (UKCMER) 2018 Annual Assembly. The digital twin model of the tidal turbine, intended to reduce uncertainty in reliability prediction, includes 5 stages: site characterisation, BEMT turbine model calibration, use of model to develop reliability indicators, predict reliability, update prediction with sensor data.

Published	Deliverable Title	Description
Sep 2018	Bayesian Reliability Modelling of a Tidal Turbine Pitch System [27]	This paper was included in the 4th Asian Wave & Tidal Energy Conference, 2018. The paper describes development of a Bayesian reliability model of a HATT pitch system using surrogate data from the wind industry. The use of Bayesian methods represents all parameters as random variables and allows for uncertainty levels to be assigned to the random variables. This paper focused on bearing, seals and electric motor as these are deemed to be critical. Levels of uncertainty in each design parameter and correction factor were quantified. Design parameters were based on HATT developer designs where possible.
June 2019	A Physics-based prognostics approach for Tidal Turbines [28]	This paper will be presented at IEEE Prognostics & Health Management 2019. A method is presented to determine the remaining useful life (RUL) of the pitch system bearing unit of a HATT device, specifically considering fatigue-life. A method is proposed for continuous update of the calculate based on loading information. Future aims are to incorporate additional components and additional failure mechanisms, and the use of operational turbine sensor data to calibrate hydrodynamic models.

4.2.2.1 Observations on TiPTORS Phase 2

As TiPTORS phase 1 focused on PTO, so has phase 2. It appears that this has been narrowed down further such that case studies are of the blade pitch system, often of bearings.

In general, TiPTORS phase 2 has adapted wind reliability methods to MEC.

Bayesian methods are used to quantify uncertainty, as they can be used with minimal data – this aligns well with MONITOR, and it will be considered whether these methods can be used within or alongside the VMEA techniques to be applied in WP4.

Start and stop conditions were not considered, which could have significant impact in operation of reliability. However, it does make sense to build a framework with fewer load cases and then expand when the framework is established.

It is interesting that rather than build the framework with the little MEC (be it TEC or WEC) data available and then refine when more is acquired, this project takes a different approach of building a framework with high fidelity wind data to later be replaced. This has advantages and disadvantages. It allows the framework to be developed to cope with the types of data that it would ultimately be desirable to use within it, and it may help to inform data gathering. On the other hand, the data may not be representative of that which could ever be acquired from a TEC device, and so the tool may need to be refined in any case. Also, it prevents the tool from being of use during the development and design stage. It does appear that this work is perhaps more focused on assessing reliability and future life of operational devices, which would inform operations and maintenance (O&M) strategies and future device development, but may not be significantly useful when developing and testing early stage prototypes.

Whilst University of Edinburgh are not project partners in this case it would be worth contacting them and/or IDCORE to further capture lessons learnt from this second phase of the TiPTORS project. It is likely that this doctorate project is nearing its end and so an overall feel for how well it has progressed, and key next steps would be useful.

4.3 SURFTEC

The 2016 – 2020 EPSRC project SURFTEC: Survivability and Reliability of Floating Tidal Energy Converters, aims to develop a design optimisation tool for floating TEC (FTEC), to improve device reliability [29]. The project has carried out numerical modelling and at-sea studies in Scotland and Canada. A coupled rigid body model (RBM) and BEMT code will be validated against at-sea measurements. Extreme loading cases will then be used to test the RBM-BEMT model. The project aims to produce design and operational strategy guidance for developers based on load predictions and estimated component fatigue life [30].

Swansea University and EMEC are both partners in this project (along with Sustainable Marine Energy (SME) and Black and Veatch) and so it should be possible to ensure that work is not duplicated and that methodologies can be shared across projects where applicable.

The project outputs to data that were found in this search are described in Table 5.

Table 5: SURFTEC Project Outputs

Published	Deliverable Title	Description
2016	SURFTEC: Survivability and Reliability of Floating Tidal Energy Converters (2016 Annual Assembly) [31]	This Powerpoint pack is believed to have been presented as a project update at the SuperGen UK Centre for Marine Energy Research (UKCMER) 2016 Annual Assembly. It provides an overview of the project aims and objectives: perform a measurement campaign, develop and validate a numerical model using BEMT to predict FTEC loading, produce an FTEC guidance document which will assist prediction of fatigue and failure in response to a range of environmental conditions.
Dec 2017	Press releases on Marine Energy Website [32]–[34]	These press releases provide updates on the deployment of SME's PLAT-I device. • PLAT-I platform harnessing Scottish tides • Strainstall loads PLAT-I tidal shackles • PLAT-I tidal platform generates first power
2018	Acquiring Flow & Movement Data on a Floating Tidal Energy Converter [35]	This poster presented at the 6th Oxford Tidal Energy Workshop, 2018, described the SURFTEC project and its ongoing work. Data from the PLAT-I device is being collected using a bespoke data logging system which includes a Nortek Vector ADV mounted above one of the turbines and recording at 64Hz, and 2 9DoF IMU sensors with accelerometers, gyroscopes and magnetometers.
2018	SURFTEC: Survivability and Reliability of Floating Tidal Energy Converters (2018 Annual Assembly) [36]	This Powerpoint pack was presented as a project update at the SuperGen UKCMER 2018 Annual Assembly. It describes the measurement campaign on the PLAT-I three-hulled SME device hosting four SCHOTTEL Hydro instream turbines. The device was deployed at Connel,

Published	Deliverable Title	Description
		Oban from late 2017 – spring 2018, and Grand Passage, Canada from autumn 2018 – spring 2019. The project aimed to obtain flow data, device loading, and device position for model validation. The 3-month Connel Bridge campaign collected 64Hz ADV data, and motion data at either 20 Hz (on SD card), or 84Hz (streamed live). The motion tracking data can be used to determine influences on the platform motion. Data collection is ongoing/recently completed. The project is determining whether to couple BEMT with WEC-Sim or OpenFAST software packages.
2018	Field Performance Testing of a Floating Tidal Energy Platform – Part 2: Load Performance [37]	This paper by SME was included in the Asian Wave and Tidal Energy Conference, 2018. It describes the sea acceptance tests (SATs) of the PLAT-I in Connel, Scotland, where there are strong tidal flows but relatively minimal waves allowing for easier access. Numerical modelling has also been carried out. The loading on the arms which lower and raise the turbines in and out of the water were higher than expected when the turbines were parked, and lower than expected when operating.

The outputs of the project state that learnings have been made regarding sensor choice and placement, so it would be interesting to see if these were applicable to MONITOR and have been or could be taken through to the project.

4.4 Others

4.4.1 RealTide

The RealTide: Advanced Monitoring, Simulation and Control of Tidal Devices in Unsteady, Highly Turbulent Realistic Tide Environments project is running from January 2018 to December 2020 and is funded under the EU Horizon 2020 programme. The project aims to identify failure causes in TECs, and to improve the design of such components alongside deploying advanced CMS and implementing targeted maintenance strategies to reduce failure instances. The project also aims to better measure turbulent flows and ocean waves to enable components to be designed with a greater understanding of environmental loading [38].

As such, this project shares many common goals with MONITOR and it would be useful to share learnings across the project. Sabella are a partner in both projects and so should be able to ensure that this happens, and that work is not duplicated. No publicly available project outputs were available at the time of conducting this review.

4.4.2 EnFAIT

The Horizon 2020 project EnFAIT: Enabling Future Arrays in Tidal is led by Nova Innovation, it started in 2017 and will run until June 2022. The project will demonstrate the installation, operation and decommissioning of the world's largest tidal array (six turbines), to reduce the cost of tidal energy and prove array reliability. Work package 9 of the project, led by SKF, will provide a benchmark of turbine reliability, and apply tools such as design FMEA to maximise tidal array reliability and availability [39].

4.4.3 OCEANERA-NET COFUND PROJECTS

Three further projects funded via the second call from The Ocean Energy European Research Area Network (OCEANERA-NET COFUND) also relate to reliability, although they have wider aims [40]. These are:

- CF2T, led by Sabella, which will test novel foundations in an aim to reduce costs and increase reliability, reducing the levelized cost of energy (LCOE) of tidal projects. The novel foundation will be compared with a classical steel foundation.
- UMACK, led by CorPower, which seeks to improve survivability, reliability and affordability of MEC through a universal anchor-foundation-mooring system. There is also future potential for use in floating wind.
- SEABLADE, led by Eire Composites, which will assess blade manufacture. The design life of turbine blades will be advanced and verified. This in turn will improve reliability of the turbine and reduce maintenance requirements, with a reduction in commercial risk in tidal projects.

5 Wider Review of Work

A wider review of published activity relating to reliability assessment and improvement of TEC devices has been carried out. There is not scope in this document to cover each item in great detail, however many published outputs have been reviewed and will be used going forward as useful reference points for the MONITOR project, in particular the WP4 VMEA activity. The findings are presented in Table 6.

It is also worth noting that a search for VMEA case studies from other industries was also carried out, but as the majority of these are already covered in other reviews these are not repeated in this report.

Table 6: Other published work related to TEC reliability

Published	Deliverable Title	Description
2005	Structural Reliability Methods (book) [41]	This is a comprehensive textbook which covers many different reliability assessment methods and the related statistics.
2009	Monitoring Ocean Turbines: A Reliability Assessment[42]	This paper considers tidal turbines 40 miles off of the Florida coast, and looks at cyclic and transient behavior for fault indications. The device CMS measures vibration, angular velocity, heat, voltage, current, cable tension, lubricant quality, and records video. Particular concerns to reliability are changing surface conditions, seasonal changes in water currents, sea turbidity and debris, corrosion, and turbulence. In terms of monitoring the device, changes in the recordings are examined rather than one specific behavior in isolation. It is highlighted that to detect rotational imbalance an array of sensors would likely be required.
2012	Simulation-based time-dependent reliability analysis for	This journal paper describes a reliability analysis method for river-based composite turbine blades which establishes the probability of failures for a given operation time. BEMT Finite

Published	Deliverable Title	Description
	composite hydrokinetic turbine blades [43]	Element Analysis (FEA) is used to establish the blade deflection response of the turbines. Key uncertainties in the model are the river flow velocities and composite material properties.
2011-2014	Reliability analysis of rotor blades of tidal stream turbines, and other associated documents[44]–[47]	One of the SuperGen Marine research programmes which has been ongoing since 2009 considers the reliability of blades in HATTs. Three methods of estimating/evaluating failure rates of TEC subsystems are first presented: 1. Use data from other industries (e.g. wind), but highlights that operational conditions are different, and that for a number of components there is not sufficient data for meaningful analysis. 2. Modify base failure rate due to changed operating parameters, which has its own uncertainties and may use unsuitable assumptions 3. Use probabilistic analysis to evaluate failure rates – develops a simple model of a generic axial flow turbine featuring an FBD The latter method was used, and uncertainties in blade loading are accounted for using probabilistic models of changes in tidal velocities. Fluctuation in these velocities is the main source of load uncertainty when assessing the likelihood of bending failure due to extreme loads (not fatigue). The work has focused on blade reliability under extreme bending loads, and accounts for uncertainties in tidal speeds, blade resistance, and the BEMT model used to calculate bending moments. The blade spar was considered, but the blade shell was not considered. Blades with pitch control are considered, and fatigue and dynamic loading were not covered in this work. The methods used would need to be modified significantly for stall-controlled device, and improvements are also suggested for pitch-controlled devices. A key point of note is that the assessment assumes the blade bending resistance does not deteriorate with time. The assessment considers a 20-year period but does not carry out fatigue analysis as it is predicted that the design is mainly influenced by extreme loading cases. Uncertain parameters of the model of component failure are treated as random variables.

Published	Deliverable Title	Description
2011 – 2018	Reducing Reliability Uncertainties for Marine Renewable Energy, Reliability assessment of tidal stream energy: Significance for large-scale deployment in the UK, and other associated work [48]–[53]	Another of the SuperGen Marine programmes, this one related to DTOcean has looked at reducing reliability uncertainties and using accelerated testing to assist with this. Work has demonstrated how accelerated testing can help to supplement the application of generic failure rate databases to offshore renewable moorings. Specifically tests for synthetic ropes and shackles were carried out. Different failure modes were seen occurring, which can provide good indications of component behavior and inform the design process. One paper which describes DT Ocean's reliability module explores two case studies, both looking at mooring fatigue testing. Mean time to failure (MTTF) calculations are used as a reliability basis. The work references TIPTORS project as being similar to SPARTA but for TEC drivetrains. Absence of a common failure database (like SPARTA) is cited as being due to lack of design convergence, use of custom-made components, and commercial confidentiality Bottom up statistical methods use existing statistical info which needs to be adjusted to change failure rates in different applications. This allows the assessment to be done with little info, but no factors have been nicely designed for MEC yet – some for electronics, O&G, military. Component reliability tests can be used to improve reliability predictions. DTOcean uses bottom-up methods, but the database can be overridden if a user has data.
2014	Tidal stream devices: reliability prediction models during their conceptual & development phases [54]	This is a thesis focusing on the comparative reliability of devices. Several papers and posters were also published, including [55]. The work proposes a method of HATT reliability prediction using historic data from wind turbines. TEC are expected to have lower reliability than wind turbines based on the outputs of this week – indeed the devices are not predicted to survive greater than a year's operation at sea. Devices with more sub-assemblies were seen to have a higher failure rate. These methods are most suited to enabling side-by-side comparison of different device concepts rather than predicting failure accurately for individual devices. RBDs are used, as is surrogate wind turbine data.
2014	A review of survivability and remedial actions of	This journal paper reviews previous work related to the survivability of TEC devices with regards to extreme weather, seabed scour, fatigue, corrosion/erosion, and marine fouling. Some key findings were:

Published	Deliverable Title	Description
	tidal current turbines [56]	• Gravity-based and tripod structures were found to be more susceptible to scour effects, and protective units to cover this area may be required. • Blades should be designed for $1x10^8$ cycles over 20 years. • Blade fouling could reduce efficiency by up to 70%.
Feb 2015	Designing for Reliability of Wave and Current Marine Energy Converters - Workshop III Report [57]	This document is a summary of a 2015 workshop funded by the US Department of Energy and Ocean Energy Systems. A total of thirteen presentations on research into ocean energy reliability were given, and the workshop considered key questions on marine energy reliability. Slide packs are included in the document, in addition to summaries from various workshop discussions. One of the featured presentations was on VMEA, and another was linked to the DTOcean project. Key points from the workshops were: • Root causes of WEC and TEC issues are not widely understood • Failure databases provide generic information, but not for the appropriate loading or environmental conditions. • Existing marine standards were deemed to be insufficient to facilitate high reliability and low cost • TEC (and WEC) reliability testing should be carried out at sea, and data recorded and released into the public domain in a database – even if some details are protected for IP reasons. • Past failures should be explored with developers – root causes should be understood and documented so much as possible. (Ensuring the difference between management and technology failures is understood).
2016	Reliability Evaluation of a Tidal Power Generation System Considering Tidal Current Speeds [58]	It was not possible to access the full paper, but from the abstract, the reliability method presented used models failure rates of rotor-side and grid-side converters based on tidal speeds. The work also identifies which operational mode carries a higher risk of failure.
2017	TiPA Project Reliability Framework - D7.2 [59]	This document proposes a framework for analyzing the reliability of TECs, particularly drivetrains. Included is a review of previous wind reliability projects and some of the other work reviewed in this report. It is suggested that a Bayesian technique would be useful if there was a limited dataset but as no deployment data is available an alternative framework is proposed. This should then be integrated into a Bayesian framework at a later date once field or lab data is available.

Published	Deliverable Title	Description
2017	Wave and Tidal Generation Devices: Reliability and Availability [60]	This book published by the IET looks to cover many of the concepts in the other individual papers – including applying offshore wind knowledge to wave and tidal generation. The full book has not been reviewed.
2018	Reliability-based design optimization in offshore renewable energy systems [61]	This paper on reliability challenges features a comprehensive review of many existing studies. The paper references a reliability database created by SuperGen including component failure rates as part of Phase 2, workstream 8. Reliability-based design optimization (RBDO) optimizes design objective using reliability constraints called limit state functions (e.g. maximum likelihood of failure). Design objectives can be random variables (mean value, coefficient of variation) which can then be used in computational optimization to represent uncertainty. For TEC – RBDO has been used for ultimate limits, not fatigue limits, and hasn't been used to develop/validate safety factors. The paper highlights the need to accurately simulate fatigue and failure over the full life of a device, in order to develop O&M strategies and understand reliability.
2018	Reliability Evaluation of Tidal Current Farm Integrated Generation Systems Considering Wake Effects [62]	This paper proposes a method for evaluating reliability of a tidal farm based on Monte-Carlo simulation techniques. This is the only work reviewed that has specifically mentioned wake effects in terms of the reliability assessment. In this method a model of tidal farm rather than a single device is used. Inputs are tidal velocity day curves, device cut-in and rated speeds and powers, and failure and repair rates for TECs. Mathematical methods are used to generate year-long tidal velocity data and to randomly generate the state of each turbine in the area for the year. Annual reliability indices (e.g. loss of load expectation) are calculated and the system works in a loop until an acceptable convergence level is reached. This appears to be a complex mathematical method, and it doesn't from this paper seek to include real information generated by devices. However, it does highlight that inclusion of turbine wake effects and tidal direction are important in reliability assessment.

It is clear from the work above that there have been many academic studies into tidal turbine reliability, but that work on reliability assessment frameworks which have been informed by field data is much more limited.

5.1 Relevant Standards

Below is a list of some of the existing relevant standards and technical specifications for marine renewable energy, in addition to some more general standards relating to design and reliability. This is not intended to be comprehensive but just to highlight some of the existing documentation. The suitability of these standards has not been assessed as part of this work.

- BS5760: Design for Reliability
- BS7000: Design Management Systems
- BS8887: Design for Manufacture
- DNV Classification Note 30.6: Structural Reliability Analysis of Marine Structures (particularly to complement ISO 2394:2015)
- DNVGL-ST-0.164: Tidal turbines
- DNV-RP-C205: Environmental Conditions and Environmental Loads
- EN 1991: Actions on structures
- EN 1993: Design of steel structures
- Guidelines for Design Basis of Marine Energy Conversion Systems *(EMEC)*
- Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems *(EMEC)*
- IEC 62600-1 Terminology
- IEC 62600-200 Performance of Tidal Energy Converters
- IEC 62600-201 Tidal resource assessment and characterisation
- IEC 62600-202 Scale testing of TEC (for publication)
- IEC 62600-2 Design of Marine Energy Converters
- IEC 62600-3 Measurement of Mechanical Loads (for publication)
- IEC 62600-4 new MEC Technical Qualification (for publication)
- ISO 2394:2015 General principles on reliability for structures (framework for risk and reliability assessment)
- ISO 13822:2010 Bases for design of structures – Assessment of existing structures (useful if re-assessing reliability as new knowledge is gained)

6 Key Findings and Next Steps

There has been significant effort to date which has gone towards investigating TEC reliability. Much of this is theoretical and requires experimental data to test the developed frameworks. Additionally, a lot of focus has been on the drive train, so MONITOR is well placed to fill in existing knowledge gaps with the proposed work plan and focus on blades and substructures.

There are a couple of additional points to note which have not been covered above:

- The RiaSoR website makes accessing all publicly available reports clear and convenient. For other projects this was not as straightforward. To maximise the impact of MONITOR it is suggested that something similar is implemented for all public documents.
- The marine/offshore environmental adjustment factors which were developed by the US military have been applied in several cases but were not developed for MEC. These allow for modification of risk and impact factors based on the environment (e.g. sheltered/unsheltered). Development of a more tailored set of TEC adjustment factors based on this could be useful for MONITOR, particularly when making the VMEA tool generic. The

user could potentially select an environment type and the tool would modify some of the factors used in calculations.

The proposed next steps in WP4 (VMEA) in order to apply the above to the ongoing MONITOR work are to:

- Review the DfR tools covered in TiPTORS in more detail in conjunction with the available data and determine which of these should be included within the project to assist with/complement the VMEA
- Work through the VMEA methodology developed in RiaSoR and select aspects most relevant to blades and substructures
- Apply these tools and methodologies to the Sabella and Magallanes devices using where appropriate:
  - lab experimental data
  - numerical model results
  - (field experimental data will be incorporated once the VMEA methodology has been further developed and field tests are complete)
- Use reference documents from RiaSoR to develop the VMEA from basic to probabilistic

The work plan will evolve further as the project progresses but at present these are the next identified activities. Outcomes will regularly be reviewed and reflected upon to ensure the VMEA methodologies being developed are fit for purpose.

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8 Appendix

8.1 Appendix 1: Table of DfR Processes from TIPTORS

Process	Cost	Resource	Complexity	Applicable	Technical Report Reference
DEFINE					
Quality Function Deployment	2	2	1	Recommended	RD.15/000418-1
Reliability Block Diagram	2	2	2	Essential	RD.15/91101.1
Reliability Allocation	2	3	2	Essential	RD.15/82201.1
IDENTIFY	2				
Change Point Analysis	1	2	1	Optional	RD.15/000517-1
FMECA	3	3	2	Essential	RD.15/104101.1
ANALYSE & ASSESS	2				
Reliability Databases					RD.15/75701.1
Physics of Failure & Condition Monitoring	3	3	3	Recommended	RD.15/141601.1
QUANTIFY & IMPROVE					
Life Data Analysis	3	2	3	Essential	RD.15/001038.1
System Reliability Analysis	2	2	2	Essential	RD.15/001038.1
Design of Experiments	3	2	3	Recommended	RD.15/001027-1
Fault Tree Analysis	2	2	2	Recommended	RD.15/001035-1
Reliability Growth	4	3	4	Essential	RD.15/001048.1
HALT / HASS /ALT	2	2	3	Recommended	RD.15/001168.1
VALIDATE	3				
Reliability Demonstration Testing	4	3	4	Recommended	RD.15/001048.1
MONITOR & CONTROL					
Root Cause Analysis	2	1	2	Recommended	RD.15/000834-1
FRACAS	3	3	2	Essential	RD.15/000875.1

Table 3 - Summary of 'Process Intensities' and Technical Report References

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