COMMISSION OF THE
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# Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

## Deliverable D5.6

# Assessment, reporting and remediation of risk associated with marine energy arrays

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## Assessment, reporting and remediation of risk associated with marine energy arrays

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### Summary

This report offers guidance for the quantification and assessment of risk associated with marine energy arrays. With all new technologies there will be issues at early stages of development involving degradation or failure with varying levels of consequence. Guidance is offered herein with regard to reducing early risk associated with the operational actions of an array hence increasing the knowledge within the industry.

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# 1. INTRODUCTION

## 1.1 GENERAL GUIDANCE APPLICABLE TO PRE-DEPLOYMENT OF ARRAYS

Risk can be defined as the combination of probability of an event occurring, and the consequence of that event occurring. In these terms, every aspect of a project can be defined with regards to its risk. The aim of managing risk is to identify what level of risk is tolerable to a project, or a company, and to ensure that all risks identified have measures applied which will maintain them at or below the level that is tolerable. This limit can be applied equally across diverse aspects of a project – financial, temporal or technical – to aid consistency in decision-making.

The assessment and quantification of risk is linked to knowledge and experience. Reducing risk or de-risking is linked to actions to minimise the consequence and reduce the probability of a specific event occurring to a component, subsystem or technology as a whole. Whilst the term risk is used extensively throughout this document it should be remembered that there is an inherent risk associated with process or action. What we are trying to achieve is a minimisation to a level that is acceptable. As our understanding and knowledge of marine energy technology increases we would also expect an increase in the technological development and a general de-risking of marine energy arrays

The development of technology is affected by the challenges from the technology itself, but also from a wider range of external factors to the technology, which are normally addressed as *enterprise risk management*. During the earlier stages of development the risks are normally focussed on the technology itself and, although the level of resources required may be very high for the developer due to the size of the enterprise, the steps taken are small and proportional to the resources available. This is normally reflected in the use of small-scale tank tests at the early stages, where a large number of investigations can be performed with low costs and failures are of a small magnitude of risk. It is still important, even at the early stages, to keep the risks under control by focussing the tests on the main parameters representing the highest risks.

Later phases – such as sea trials and multi-device arrays – will require higher investment for large-scale tests (typically orders of magnitude more expensive) and development of deployment methods. The risks too are higher because of the move from the controlled laboratory environment to the uncontrolled natural environment: the environmental loads can be extreme and there can be long expensive waiting times for favourable weather windows for tests and attendance to the device for repairs. There are also social and business risks; e.g. a failure may become public, leading to loss of reputation, affecting relations with investors and other stakeholders, and affecting the industry in general, not just the particular developer.

Progressing to the commercial stages, pressures are now related to serial production and contractual exposure. The technology and its deployment are still important, but are now rivalled by factors from the enterprise side. Although now a developer has a much larger capacity for investment, most of the investment is likely to be focussed on improving efficiencies related to serial production, reliability and energy capture and conversion. This phase is related to the pre-commercial stage and related to the deployment of arrays.

## 1.2 EXPERIENCE OF RISK LEADING UP TO ARRAY–SCLAE DEPLOYMENT

It is almost certain that device developers will have experience of risk assessment from sea trials. Depending upon legislative conditions imposed by the country of deployment some method of certifying or verifying the performance and integrity of a device will have been conducted in order that it can be deployed offshore. However, there are clear differences between sea trials (initial deployments) and larger multi megawatt deployments. An array of devices in close proximity is clearly different offering greater power output, occupying a larger spatial area and with the propensity for interaction between devices. This increase in size and complexity will lead to the design and operational parameters of the individual devices within the array evolving hence ensuring changes in risk will occur.

# 2. RISK REPORTING AND REMEDATION

## *2.1 QUANTIFICATION OF RISK FOR FUTURE ARRAY TECHNOLOGY*

The following set of Technology Readiness Level (TRL) descriptions are commonly applied to development of new technology to describe the stages in the development process. These descriptions have been adapted to marine energy systems, and the process of tank tests, sea trials and full scale multi-device arrays which is the basis for the engineering strand of Equimar. The TRLs can be related to the overall system, or to a component within the system. When assessing the TRL it is important to consider the environment and the application that the system is operating in, versus what it has been developed in. For example, at present, gearboxes are used normally in dry environments with an inspection and maintenance frequency of between 6 months and 1 year. If the gearbox is to be submerged, or is subject to less frequent maintenance, the TRL would be reduced from 9 to as low as 5 or 6 depending on the application.

| Technology Readiness Level | TRL definition | Description |
|---|---|---|
| TRL 1 | Basic principles observed and reported | Scientific research beginning to be translated into applied R&D. Initial proposal of concept derived from observations of physical principles. |
| TRL 2 | Technology concept and/or application formulated | Paper and analytical studies of technology applied in marine environment. |
| TRL 3 | Analytical and experimental critical function and/or characteristic proof of concept | Active research and development is initiated, including analytical studies and laboratory tests / tank tests to physically validate the analytical predictions. Parts of the system may be representative tested, such as use of discs instead of rotors, or orifice plates instead of air turbines. |
| TRL 4 | Component and/or system validation in laboratory environment | The basic technological components are integrated at the laboratory scale to establish that the pieces will work together. The outputs should be analyses of how the experimental test results differ from the expected system performance goals. |
| TRL 5 | Laboratory scale, similar system validation in relevant environment | |
| TRL 6 | Engineering/pilot scale, similar (prototype) system validation in relevant environment | Engineering scale models tested in a relevant environment. Outputs should include a comparison between the predicted analytical results, and the results from the trials. |
| TRL 7 | Full-scale, similar (prototype) system demonstrated in relevant environment | Demonstration of system operating in relevant environment, such as full scale prototype operating for a number of months and developing and improving operating procedures and settings. |
| TRL 8 | Actual system completed and qualified through test and demonstration | The technology has been proven to work in its final form and under expected conditions, such as with a full scale prototype in similar configuration to the final machine operating for a number of years to demonstrate continued operation and reliability. |
| TRL 9 | Actual system operated over the full range of expected conditions. | The technology is in its final form and operated under the full range of operating conditions, in a multi-device array configuration. |

As the TRLs cover a wider range of development than is expected for array deployments we can express the level of understanding, experience and application on a more applicable scale. Figure 1 illustrates one such method, no doubt other methods exist or will evolve in the future.

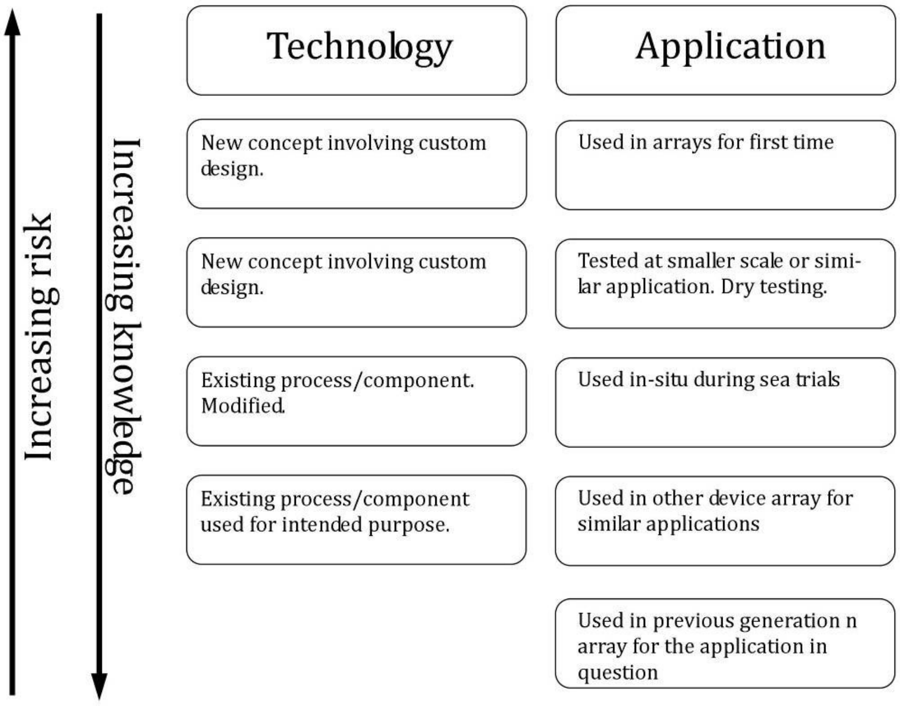


**Figure 1** – Method for evaluating technical risk associated with elements of marine energy arrays

The use of TRLs offers a method of communicating between stakeholders the current stage of development / maturity of the technology and where it will move to in the future. TRL is, in a broad sense, an indicator of potential risk for success of technology, but it does not actually indicate the risk involved with the technology at that stage. Other methods can be developed and shown (Fig. 1). At best a device can utilise existing components and processes but apply them in an environment that has not been experienced before. Thus it is the forward-looking or predictive risk that is most difficult to quantify. It follows that as experience and knowledge grows for a particular area of technology and application so the risk can be more accurately quantified. This can be expressed by metrics such as Mean Time Before Failure (MTBF) for a component used under specific conditions. Such expressions are based upon a large amount of data and can allow scheduled maintenance or replacement before degradation or failures occur. This will become more prevalent as arrays evolve from small demonstrator installations to large multi-megawatt arrays.

## 2.2 FAILURE MODE AND EFFFECT ANALYSIS

The main principle of a Failure Mode and Effects Analysis (FMEA) is to identify individual modes of failure for the components within a system and investigate the effects of these failures. This can be developed into a risk analysis by combining the consequence of a failure with its probability to produce an assessment of risk.

A normal approach to an FMEA is to begin by breaking down the system into components with functions. The level of definition and detail here should be defined based on the components in question. For example, it is not normally necessary to go down to the level of nuts and bolts. The function for each component should be described, as this helps to understand the nature of a failure and its consequences for the system as a whole. An abridged example of the tree or cascading nature of an array is illustrated in Figure 2.

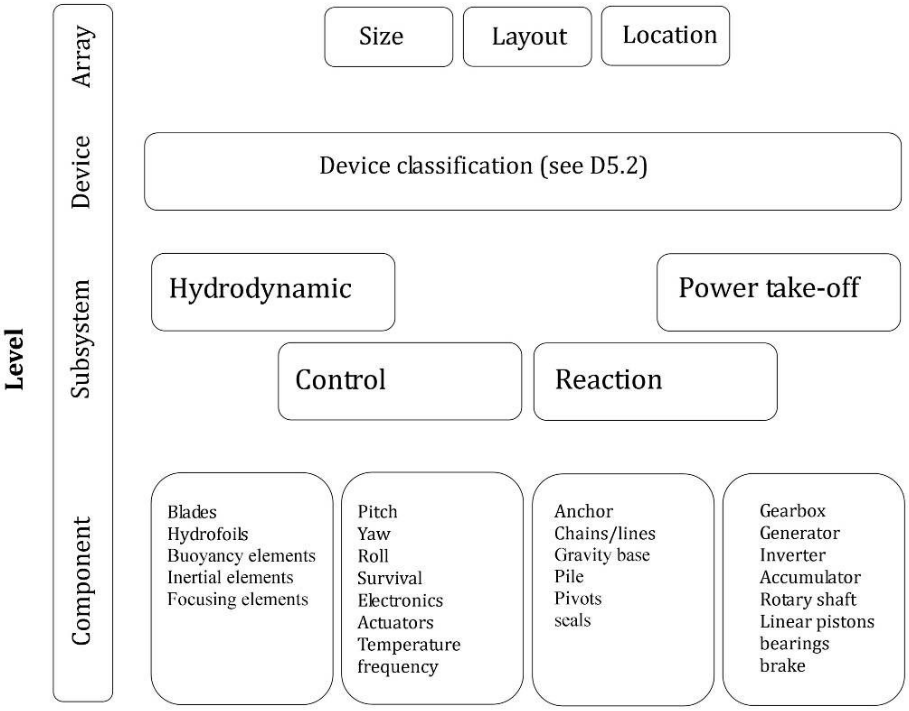


**Figure 2**– Example of the tree structure approach required for identification of risk

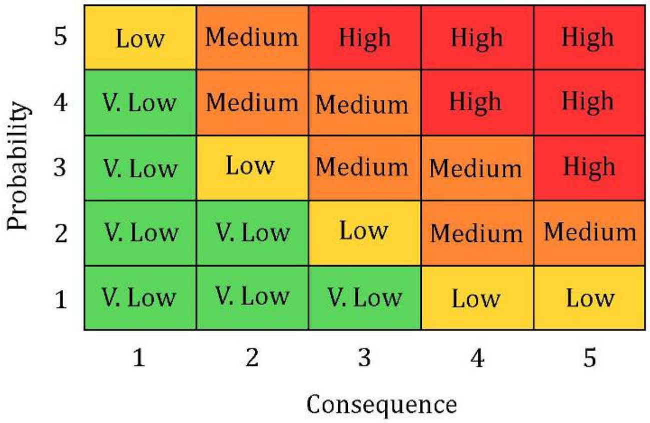
Once the system has been broken down, the process is the same for each component. First, the potential failure modes should be identified. For example, when analysing structures, this may include buckling, yield and fatigue. For each failure mode the mechanisms that may lead to that failure should be identified – there may be several for each failure mode. For example, fatigue failures can be caused by Vortex Induced Vibrations, or by unbalanced loading in rotating equipment.

For each failure mode and mechanism combination, the consequence of the failure should be identified. For a failure mode, the consequence will generally be the same, regardless of the mechanism leading to failure. At this point, it is also important to investigate any means of detection of a failure that have been designed into the system, such as leak detectors in jacket structures which can be used to detect small cracks. These should be investigated, along with any other means of limiting the consequences of failure.

While FMEA is useful as a systematic method of considering all possible failures in a system from an early stage, its usefulness can be enhanced by adding an assessment of risk, producing a Failure Modes, Effects and Criticality Analysis (FMECA). Once the above steps are completed, the consequence can be given a ranking based on a pre-defined set of descriptions for different levels of severity. For example, considering safety, a negligible consequence may be given a class of 1, while a failure resulting a fatality may be given a class of 5. Everything in between is rated accordingly. It is often useful to assess the consequence in terms of cost as this can help to remove subjectivity. If this is done there should be a consistent step between consequence classes, such as an order of magnitude.

The probability of failure is also required to be assessed. This can be different for different failure mechanisms. Note that this is not an assessment of the probability of a particular consequence occurring, and a conservative method is to assume that the worst case consequence occurs for a particular failure (assuming all consequences are equally likely). Normally, only one level of failure should be assumed, combinations of failures can be neglected assuming that their individual probabilities are relatively low. The exception to this is systems and components which exist only to protect the machine in case of failure of another part.

Once the consequence and probability have been assessed, these can be combined to produce a measure of risk. This can be done using a risk matrix, or by using Risk Priority Numbers. Both of these approaches are discussed in detail elsewhere. The method used should provide a clear definition of the tolerability of risk, so that the risks identified in the FMECA can be defined as acceptable or unacceptable. The principle is that unacceptable risks should have an action assigned which is capable of reducing the risk to as low level as reasonably practicable.



| Probability | | | | | |
|---|---|---|---|---|---|
| 5 | Low | Medium | High | High | High |
| 4 | V. Low | Medium | Medium | High | High |
| 3 | V. Low | Low | Medium | Medium | High |
| 2 | V. Low | V. Low | Low | Medium | Medium |
| 1 | V. Low | V. Low | V. Low | Low | Low |
| | 1 | 2 | 3 | 4 | 5 |
| | Consequence | | | | |

**Figure 3** – FMEA risk matrix

The descriptive elements that are formed by the product of the probability and consequence in a risk matrix are not fixed. The key objective for a device developer or array operator is to define where the tolerance of risk lies. This will be project-specific based on the acceptable combinations of consequence and probability as they have been defined by the developer. For example, a level of risk deemed Low (Fig 3) may relate to a specific cost for repair so the array operator would need to decide on how often such a cost can be accepted. The probability classes where this cost is tolerable can be used to define the limitation of risk tolerance. In this way tolerance for any consequence and following actions can be related to the descriptive category on the risk matrix.

One final aspect of FMEA or FMECA is the issue of minor faults in one component/subsystem etc. causing following faults in others. Such a scenario can rapidly escalate with critical consequences. Such a process is termed ‘avalanche’ or ‘cascading’ failures. Potential failure paths should be identified as a matter of great importance. Remediating actions can include greater efforts of reliability or fault detection along a specific fault path to prevent a cascade failure from either occurring or propagating beyond a certain point. Such issues are addressed later in this document.

# 3. RISK REDUCTION ACTIONS

Several means are available to reduce and/or limit risks identified in a system. The primary methods are to reduce or limit the consequence of failure, or to reduce the probability of failure. With novel technology and novel applications such as wave and tidal energy systems, uncertainties also often contribute to the risk, particularly with respect to probability of failure. Further means of reducing the risk are therefore by performing tests and performing more detailed analyses.

Consequences of failure can be limited in wave and tidal energy systems in several ways. The following list is for example only, and is not exhaustive:

- Development of automatic shutdown strategy to prevent further damage caused by a failure;
- Inclusion of redundant systems to reduce downtime caused by a failure;
- Design of protection systems to prevent runaways caused by failures (e.g. including a ‘weak link’ or a clutch on a rotating system to prevent over-torque and over-speed respectively);
- Movement of critical equipment to an accessible location where possible, such as a transformer platform used in offshore wind farms.

Probabilities of failure in wave and tidal energy systems can be limited by the normal methods. A list of examples is given below:

- Increasing design factors (if using Load and Resistance Factor Design) on structural members to reduce probability of strength-related failures;
- Increasing design fatigue factors to increase fatigue life of a structure;
- Including weak-link or a clutch in rotating machinery to limit loading on the drive train;
- Development of a ‘survival mode’ to limit the exposure of the machine to extreme loads;
- Develop a condition monitoring system which allows loads to be limited based on condition of equipment;
- Increase inspection and replacement frequency;
- Reduce exposure to degradation mechanisms, e.g. seal components from contact with water, improve coating to reduce corrosion, burial of cables;

Some of the drivers for the actions/approaches listed above are discussed in the following sections.

## 3.1 *GUIDANCE ON ASSESSMENT AND REDUCTION OF RISK FOR ARRAYS*

Risk assessments on marine energy devices are normally conducted considering the device in isolation, especially during the development of the technology where only one device is likely to be deployed at any one time. However, the risk assessment should also be used to analyse the risks associated with operation of multi-device arrays. In fact, this should be completed initially at an early stage in the development process in order to guide the collection of data from different stages and tests.

While arrays can bring higher risks in terms of contractual pressures and finances, there are also several solutions and methods of risk reduction available which would not be applicable to single devices.

### *3.3.1 Risk detection*

Detection of faults is often a most advantageous design strategy. Smaller faults can cascade to lead to larger more complex faults that may well have much more serious consequences. For this reason risk detection is of great importance and detection should be placed on all components and systems whose failure might lead to an unacceptable increase in risk based upon the risk matrix (Figure 3).

For devices at sea trials it is worth fixing faults rapidly before the consequences become more critical and lead to larger failures. For arrays upon device fault detection a different approach might be employed whereby the device’s operational envelope is reduced so as to prevent the fault cascading or requiring immediate corrective actions. Another route would be to take the device offline completely and to effectively hibernate. Both these actions could facilitate more cost-effective corrective maintenance to be applied or for the devices to operate at zero or partial performance until a scheduled maintenance interval is reached.

### *3.3.2 Design*

At the uppermost level the design of an array by definition is likely to be different from that of an equal number of isolated devices. There is opportunity for shared subsystems. In order for these to be viable there are a number of drivers such as financial and technical improvements over and above the individual systems that the shared unit replaces. A further factor is reducing the risk associated with a single shared subsystem. Replacement, repair should be cheaper and easier but the opportunity for a lower risk design (compared to the several systems it replaces) should also not be discounted.

Remaining at array scale the design of purpose-built support and maintenance vessels can aid the reduction of risk and reduce deployment and operational costs. Designing a vessel with increased operational window would facilitate maintenance actions in more extreme conditions that otherwise might prevent scheduled or corrective actions for potentially long periods of time. The higher cost of a specialist vessel might be offset by the fact that it is not available for other offshore work thus the availability to the array is maximised. This could be most beneficial when corrective (unscheduled) maintenance is required.

At the device level redesigning of components can achieve a reduction in risk. Measures to increase the strength or the level of pretention (such as sealing) of parts can lead to reducing scores on a risk matrix. Redesigning subsystems can allow cheaper smaller vessels to deploy and maintain devices within an array and can be viewed as an alternative to developing specialist vessels.

Designing redundancy into any level system of the array is a further method for reducing risk. One example is to have a number of separate electrical generators that all operate under maximum load. If one unit fails then the power can be absorbed by the remaining units. This approach would then allow the fault to be repaired during scheduled maintenance rather than requiring an unscheduled action, reducing device power output or triggering the device to go offline. Redundancy can reduce the consequences of a failure such that learning is achieved and redesign is possible at a later stage.

### *3.3.3 Scheduled/periodic maintenance*

This course of action involves replacing components close to failure (MTBF) at scheduled periods. Replacing components in advance of any failure allows wear to be assessed (on shore) and redesign or improvement of parts if required. Periodic maintenance can be used in conjunction with fault detection to replace or repair components that were not scheduled but have been detected as requiring action. Determination of a scheduled maintenance programme will be dependant upon the costs (and risk) associated with maintenance actions for a particular device type and parameters of the specific array. Scheduled maintenance is effectively a hedge against subsequent failure that would require corrective maintenance (addressed below).

### *3.3.4 Corrective/reactive maintenance*

Here component/systems etc. are replaced or repaired following failure. The action is not planned (as with scheduled actions) and therefore implies that the fault is worth correcting because:

- It is financially beneficial to do so
- The failure might affect other aspects of the array (cascade failure)

Corrective maintenance for the first reason will depend upon the cost/benefit of replacing the component/system in question. For example if it is a common PTO system shared between a number of devices then the lost revenue might outweigh the costs associated with mobilising and deploying a vessel to replace the system.

The second reason is likely to involve the safety of the array and other users of the sea. In this case there is a moral (and legal) obligation to repair the fault. An example could be the failure of catenary moorings on a floating wave energy converter causing it to break free and drift. This could cause a collision with other devices in the array (cascade failure) or with other sea going vessels. The key issue with corrective maintenance at array scale installations is that knowledge is acquired in order that such actions are not required in future. This could be through better fault detection or design.

# 4. GUIDANCE ON REPORTING OF RISK

Collection of array performance, operation and maintenance logs and reliability data from arrays is extremely important for validating risk models and acquiring knowledge such that risk is continually reduced. There is no established standard at present for marine energy arrays. The development of such reporting methods is best achieved by doing and as such will evolve with arrays. ISO 14224 (Petroleum, petrochemical and natural gas industries — Collection and exchange of reliability and maintenance data for equipment) is a good starting point for how to collect and report reliability data and could be adapted to serve the marine energy industry.