Marine Energy Technology Development Risk Management Framework

David Snowberg, Ritu Treisa Philip, and Jochem Weber

National Renewable Energy Laboratory

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List of Acronyms

ABS	American Bureau of Shipping
AFR	annual failure rate
API	American Petroleum Institute
ARL	adoption readiness level
CARAT	Commercial Adoption Readiness Assessment Tool
CBS	cost breakdown structure
CLASS	classification of risk
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency & Renewable Energy
EHS	environment, health, and safety
EMEC	European Marine Energy Centre
FMEA	failure modes and effects analysis
FMECA	failure modes, effects, and criticality analysis
IEC	International Electrotechnical Commission
IECRE	IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications
IMPCT	risk impact
LCOE	levelized cost of energy
MEC	marine energy converter
MRL	manufacturing readiness level
NREL	National Renewable Energy Laboratory
OES	Ocean Energy Systems
PMBOK	Project Management Body of Knowledge
PMI	Project Management Institute
RBS	risk breakdown structure
RPN	risk priority number
SOP	safe operating procedure
TBD	to be determined
TPL	technology performance level
TRL	technology readiness level
TS	technical specification
TQ	technology qualification
TQP	technology qualification plan
WEC	wave energy converter
WPTO	Water Power Technologies Office

Executive Summary

Over the past decades, the global marine energy industry has suffered a number of serious technological and commercial setbacks. To help reduce the risks of industry failures and advance the development of new technologies, the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory developed a Marine Energy Risk Management Framework in 2015 [1]; this 2024 publication is a revision to that framework. This risk management framework shall be used on all DOE Water Power Technologies Office (WPTO) projects that require system testing in the open water.

By addressing uncertainties, the marine energy risk management framework increases the likelihood of successfully developing marine energy converter technology. It covers projects of any technology readiness level or technology performance level and all risk types (e.g. technological risk, regulatory risk, commercial risk) over the development cycle.

This risk framework is not a substitute for other risk management procedures that may be required for marine operations, such as installations at sea, hoisting and rigging, safe diver operations, and other safety requirements.

This risk framework is intended to meet DOE's risk management expectations for marine energy technology research and development efforts from WPTO. It also provides an overview of other relevant risk management tools and documentation.[1]

This framework emphasizes design and risk reviews as formal gates to ensure risks are managed throughout the technology development cycle. Section 1 presents the recommended technology development cycle, Sections 2 and 3 present tools to assess the technology readiness level and technology performance level of the project, respectively. Section 4 presents a risk management process with design and risk reviews for actively managing risk within the project, and Section 5 presents a detailed description of a risk registry to collect the risk management information into a living document. Section 6 presents a method to analyze system failure modes through a failure modes effects and criticality analysis. Section 7 presents recommendations for collecting and using lessons learned throughout the development process.

[1] Embedded hyperlinks (underlined text) to external references are included. The long-term integrity of these external links cannot be ensured. If hyperlinks are not functioning, consult the References section for the formal reference.

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1 Technology Development Flowchart

Figure 1 contains a flowchart of a typical development cycle used in marine energy converter (MEC) component-level, subsystem-level, and system-level design and testing. The steps and decision gates are defined in Section 1.1. For developing individual components or subsystems in parallel to a full system, the processes in Figure 1 should be applied separately for each development.

The technology readiness level (TRL) basis for this development process enables scaled development of MEC technology toward a commercial product. This process allows for both the development of small-scale commercial systems (TRL 9) and small-scale protype systems (TRL 6) to be a progression toward a larger commercial system. For example, one company may be working to develop a commercial product (TRL 9) that is rated for 1 megawatt (MW), whereas another company may be developing a 10-MW commercial product (TRL 9) for which 1 MW is a 1/10 prototype (TRL 5). The size and cost of the system is independent of its TRL.

The technology performance level (TPL) basis for this development process relates to the techno-economic performance of the technology, which is an indication of the commercial *viability* of the product. There may be new risks related to changes in TPL, which is the reason it is included in the Figure 1 development process.

There are many other methods to quantify and guide the development of new technology. The adoption readiness level (ARL) is a framework to drive technology commercialization by the U.S. Department of Energy's (DOE's) Office of Technology Transitions [2]. The Commercial Adoption Readiness Assessment Tool (CARAT) provides an approach to combine TRLs with ARLs toward commercialization outcomes [3]. A manufacturing readiness level (MRL) is a way to quantify manufacturing maturity; the MRL guide from the U.S. Department of Defense is referenced as an example [4]. DOE's Advanced Research Projects Agency-Energy has published a template for planning the advancement of technology to the market [5]. Any of these technology development metrics and guidelines could be used as a complement or in place of the TRL and TPL approach described in this marine energy risk framework.

The technology development flowchart may overly simplify how a development process will actually occur; it is not intended to be a prescriptive process. The primary intent of this flowchart is to show that risk management and lessons learned should be integral to the technology development process.

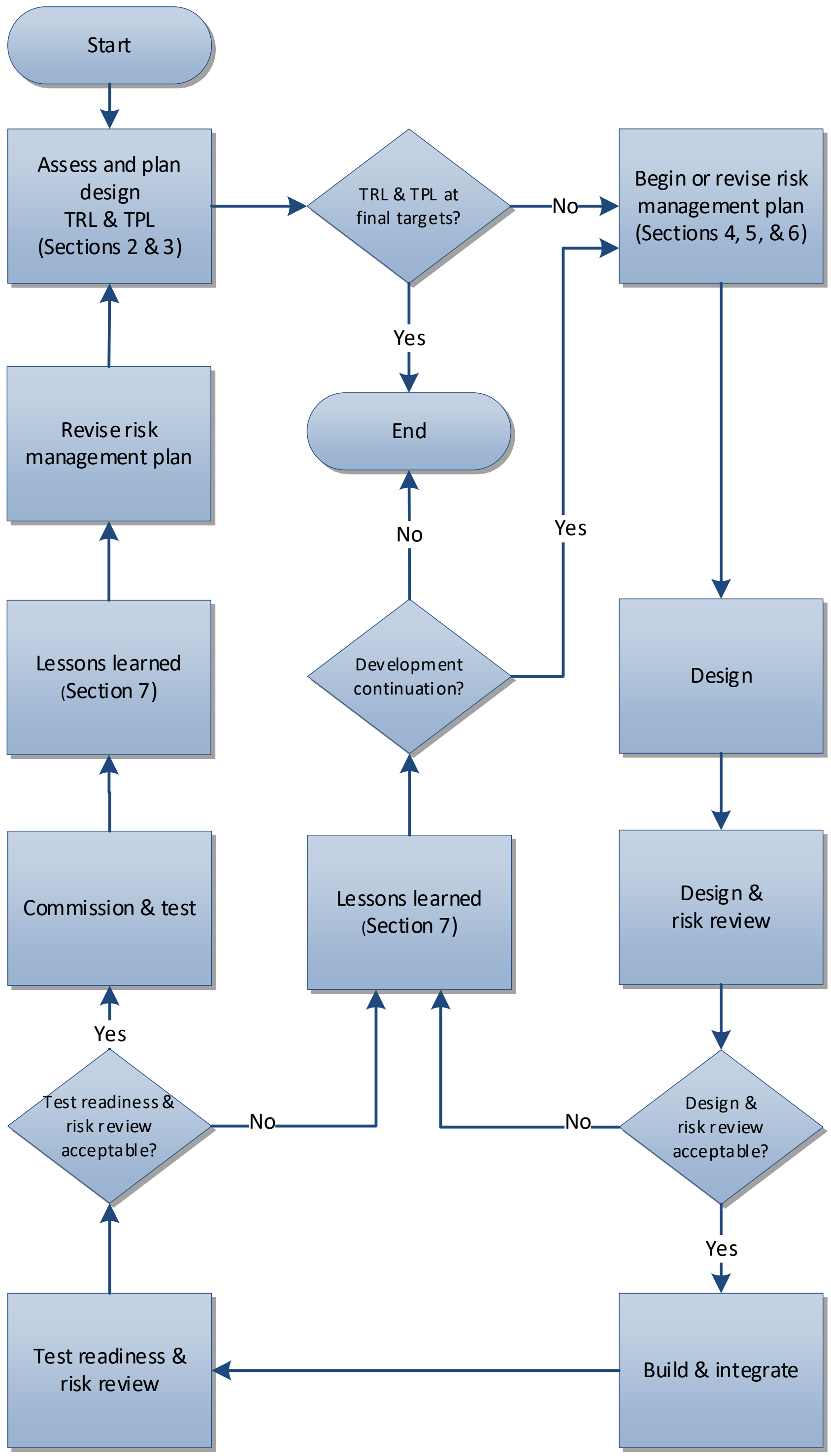

Figure 1. Risk management in the MEC technology development flowchart

1.1 Flowchart Processes and Decision Gates

Assess and plan design TRL and TPL. Categorize the current TRL and TPL for the system and/or its components. The plan is the incremental TRL and TPL targets for subsequent development cycles. See Table 1 in Section 2 and Table 2 in Section 3 for details on assessment criteria.

TRL and TPL at final targets? Determine if the existing TRL and TPL values for the system and/or its components have reached the final targets.

Begin risk management. Develop and begin implementing a risk management plan (Section 4.1). This risk management framework shall be used on all WPTO projects that require system testing in open water. The risk management requirements at each TRL are detailed in Table 3. The risk management plan shall be based on this marine energy risk management framework document. **The process of identifying, analyzing, monitoring, and controlling risks continues throughout the development cycle (Figure 1).**

Design. Design the system and/or its components.

Design and risk review. Prior to build and testing, review the design and risks. All of the pertinent Table 3 items should be reviewed during this process. The review should be based on (1) design with documentation and models, (2) risk management completion per Table 3, and (3) acceptable risk management results. It should be noted that Table 3 requires completion of both a risk register and a failure modes, effects, and criticality analysis (FMECA) for TRL 4 and above.

Design and risk review acceptable? Determine if the design and risks are acceptable.

Development continuation? For failed decision gates, determine if the technology development should continue after capturing lessons learned. To do this, evaluate the identified negative risks (threats) and costs of the project against the positive risks (opportunities) and benefits. A decision to not continue development moves to the termination of the project short of the TRL or TPL goal, and a decision to continue returns to the cycle's risk management planning stage.

Build and integrate. Build and integrate the components and subsystems for testing. The International Electrotechnical Commission (IEC) technical specification (TS) 62600-103 and IEC TS 62600-202 provide recommendations for testing pre-prototype devices [6] [7].

Test readiness and risk review. Review the built and integrated system and/or components/subsystems before testing. This process should include a risk review with particular emphasis on the technology qualification plan. All of the pertinent Table 3 items should be reviewed during this process. Review should be based on (1) verification showing built equipment is the approved design, (2) risk management completion per Table 3, and (3) acceptable risk management results.

Test readiness and risk review acceptable? Decide if the system or components are ready for testing. This review can be a go/no-go gate.

Commission and test. Execute the test plan at the system level and/or the component/subsystem level.

Lessons learned. Gather lessons learned to formalize institutional learning. Identify specific problems and recommendations to avoid reoccurrence, successes that can be used in the future, and risk management improvements. Section 7 provides additional details for documenting lessons learned.

Revise risk management plan. Revise the risk management plan (Section 4.1) based on information documented during the lessons learned process. The risk management plan is modified to ensure it continues to be valuable for the team.

2 Assess Technology Readiness Level Process

TRL definitions are used to assess the commercial readiness (technology maturity) of the marine energy technology and to guide the technology development cycle. Table 1 contains the TRL definitions from the DOE *Technology Readiness Assessment Guide* [8], and the DOE Office of Energy Efficiency and Renewable Energy (EERE) EERE R 540.112 02: Technology Readiness Levels document [9].

Table 1. Technology Readiness Level Guideline [8] [9]

Relative Level of Technology Development [8]	Technology Readiness Level (TRL)	DOE EERE TRL Definitions [9]	DOE EERE TRL Description [9]
System Operations	TRL 9	Actual system operated over the full range of expected mission conditions [8].	The technology is in its final form [8].
System Commissioning	TRL 8	Actual system/process completed and qualified through test and demonstration.	Pre-commercial demonstration: End of system development. Full-scale system is fully integrated into operational environment with fully operational hardware and software systems. All functionality is tested in simulated and operational scenarios with demonstrated achievement of end-user specifications. Technology is ready to move from development to commercialization.
	TRL 7	System/process prototype demonstration in an operational environment.	Integrated pilot (system): System prototyping demonstration in operational environment. System is at or near full scale (pilot or engineering scale) of the operational system, with most functions available for demonstration and test. The system, component, or process is integrated with collateral and ancillary systems in a near-production-quality prototype.
Technology Demonstration	TRL 6	System/process model or prototype demonstration in a relevant environment.	Beta prototype (system): Prototyping implementations are partially integrated with existing systems. Engineering feasibility fully demonstrated in actual or high-fidelity system applications in an environment relevant to the end user.
Technology Development	TRL 5	Component and/or process validation in relevant environment.	Beta prototype (component): Thorough prototype testing of the component/process in relevant environment to the end user is performed. Basic technology elements are integrated with reasonably realistic supporting elements based on available technologies. Prototyping implementations conform to the target environment and interfaces.
Technology Development	TRL 4	Component and/or process validation in laboratory environment.	Alpha prototype (component): Stand-alone prototyping implementation and testing in laboratory environment demonstrates the concept. Integration and testing of component technology elements are sufficient to validate feasibility.

Relative Level of Technology Development [8]	Technology Readiness Level (TRL)	DOE EERE TRL Definitions [9]	DOE EERE TRL Description [9]
Research to Prove Feasibility	TRL 3	Analytical and experimental critical function and/or characteristic proof of concept.	Proof of concept validation has been achieved at this level. Experimental research and development is initiated with analytical and laboratory studies. System/integrated process requirements for the overall system application are well known. Demonstration of technical feasibility using immature prototype implementations are exercised with representative interface inputs to include electrical, mechanical, or controlling elements to validate predictions.
	TRL 2	Technology concept and/or application formulated.	Applied research activity. Theory and scientific principles are focused on specific application areas to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
Basic Technology Research	TRL 1	Basic principles observed and reported.	Scientific problem or phenomenon identified. Essential characteristics and behaviors of systems and architectures are identified using mathematical formulations or algorithms. The observation of basic scientific principles or phenomena has been validated through peer-reviewed research. Technology is ready to transition from scientific research to applied research.

3 Assess Technology Performance Level Process

The TPL metric is complementary to the TRL metric; it is used to quantify the techno-economic performance potential of a technology [10]. The combination of TRL and TPL provides a complete representation of the status of technology under development toward commercial readiness and economic viability and serves as a set of metrics to quantify and assess development progress. Development steps targeting the improvement of technology performance may be quantified by a TPL [11], or another techno-economic performance metric.

Table 2 contains the TPL definitions [12].

Table 2. Technology Performance Levels – Categories and Characteristics [12]

TPL	Category	Characteristic	TPL Characteristics
9	high	Technology is economically viable and competitive as a renewable energy source.	Competitive with other energy sources without any support mechanism.
8			Competitive with other energy sources given sustainable (e.g., low feed-in tariff) support mechanism.
7			Competitive with other renewable energy sources given favorable (e.g., high feed-in tariffs) support mechanism.
6	medium	Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.	Majority of key performance characteristics and cost drivers satisfy potential economic viability under distinctive and favorable market and operational conditions.
5			To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation improvements are required and regarded as possible.
4			To achieve economic viability under distinctive and favorable market and operational conditions, some key technology implementation and fundamental conceptual improvements are required and regarded as possible.
3	low	Technology is not economically viable.	Minority of key performance characteristics and cost drivers do not satisfy potential economic viability, and critical improvements are not regarded as possible within fundamental concept.
2			Some key performance characteristics and cost drivers do not satisfy potential economic viability, and critical improvements are not regarded as possible within fundamental concept.
1			Majority of key performance characteristics and cost drivers do not satisfy and present a barrier to potential economic viability, and critical improvements are not regarded as possible within fundamental concept.

4 Risk Management Process

Table 3 contains the TRL-specific risk management activities to be completed for each technology development cycle. Each item within this table is described in subsequent subsections. The order of activities in Table 3 approximates the flow within a development cycle (Figure 1).

References from the IEC technical specifications are given in Table 3 because these international standards help define risk management activities for marine energy technology development. Also, following a robust risk management approach as described in this framework will help a developer prepare for certification to relevant IEC standards. The IEC standards for marine energy are from the IEC Technical Committee 114 (TC 114), which consists of a suite of internationally developed consensus-based standards focused on marine energy from water, tidal, and other water current converters [13]. The IEC Electropedia (also known as IEV Online) Part 417 provides definitions to all terminology in the IEC marine energy standards [14], which has replaced IEC TS 62600-1 [15]. Appendix A contains a list of the current design and testing standards from IEC TC 114.

Table 3. Risk Management Activity as a Function of TRL

Activity Required at TRL Level									Risk Management Activity	IEC References	Section
1	2	3	4	5	6	7	8	9			
x	x	x	x	x	x	x	x	x	Risk management plan		4.1
x	x	x	x	x	x	x	x	x	Project plan		4.2
		x	x	x	x	x	x	x	Technology qualification	IEC TS 62600-4	4.3
x	x	x	x	x	x	x	x	x	Risk register		4.4
			x	x	x	x	x	x	Failure mode effects and criticality analysis (FMECA)	IEC TS 62600-4 IEC 60812	4.5
x	x	x	x	x	x	x	x	x	Design basis	IEC TS 62600-2	4.6
x	x	x	x	x	x	x	x	x	Design basis – requirements	IEC TS 62600-2	4.6.1
			x	x	x	x	x	x	Design basis – loads	IEC TS 62600-2 IEC TS 62600-3	4.6.2
			x	x	x	x	x	x	Design basis – design description		4.6.3
			x	x	x	x	x	x	Design basis – design analysis	IEC TS 62600-2	4.6.4
			x	x	x	x	x	x	Design basis – define survivability, reliability, and maintainability targets and strategies	IEC TS 62600-2 (Section 6 & 12.9)	4.6.5
x	x	x	x	x	x	x	x	x	Design basis – environmental, health, and safety		4.6.6
x	x	x	x	x	x	x	x	x	Lessons learned		4.7

4.1 Risk Management Plan

The risk management plan defines how risk management is conducted throughout the development cycle. This marine energy risk management framework may provide the foundation for the risk management plan. The plan should be a living document to be continuously updated throughout the project with a focused update after each development cycle to integrate lessons learned (see Section 4.7). The Project Management Institute's (PMI's) standard for risk management is a useful reference when developing a risk management plan [16], as is the ISO 31000 risk management guideline [17] [18].

4.2 Project Plan

The project plan describes how the project will be managed during the development cycle. This plan reduces negative risk impacts by considering and managing all the dynamic elements influencing the project. The level of detail for the project plan is commensurate with project complexity. PMI's Project Management Body of Knowledge (PMBOK Guide) is a useful reference when developing a project plan [19]. A project plan should have dedicated sections for the environmental, health, and safety (EHS) plans and requirements for the project [20]. The plan for managing environmental impacts and aspects should be contained within the project plan [21].

4.3 Technology Qualification

Technology qualification (TQ) is the overall process to validate that the MEC technology will reliably perform under stated conditions. Relevant health and safety factors for the technology should be considered throughout the TQ process. The technology qualification plan (TQP) outlines the steps to verify the technology has met the design requirements and targets. A wide range of tasks and activities, including tests, may be required to complete the TQP. A Statement of Feasibility is a third-party verification from a certifying body indicating the approval of the TQP.

The TQ for MEC technology should comply with the requirements in IEC TS 62600-4 (technology qualification) [22], with the following suggested stages:

- A TQP should be developed in accordance with IEC TS 62600-4 for systems that will achieve TRL 5 (or above) by the conclusion of the project.
- A Statement of Feasibility should be obtained from a certifying body in accordance with IEC TS 62600-4 for systems that will achieve TRL 6 (or above) by the conclusion of the project.

The Lloyd's Register Guidance Notes for Technology Qualification outlines a path to certification to IEC standards through the technology qualification process [23]. The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) provides an overall certification system to IEC renewable energy standards that includes TQ and more [24]. Separate from IEC standards, Det Norske Veritas (DNV) has developed their own technology qualification process through DNV-RP-A203 [25].

Test plans are a subset within and should describe the procedure for obtaining data to satisfy the TQP. All relevant IEC 62600 testing standards developed through the IEC TC 114 should be considered [13]. The Equimar Protocols for assessing marine energy converters should be used when developing a test plan [26]. Also, a wave energy converter (WEC) test plan should consider the recommendations outlined in the International Towing Tank Conference Guideline for model test experiments [27] and the Ocean Energy Systems (OES) Guideline for testing systems [28]. All reported measurements should have an estimated uncertainty that complies with the Guide to the Expression of Uncertainty in Measurement [29].

4.4 Risk Register

The risk register is a list of all uncertain events that could have a positive or negative impact on the marine energy technology development. The risk register contains prioritized risks along with a response plan for each risk. A risk register should contain risk names, risk owners, severity of impact assessments, probability assessments, risk priorities, and response plans. Additional risk register details are contained in Section 5. The cover page for this report contains a link to a risk register template [30].

4.5 Failure Modes, Effects, and Criticality Analysis

FMECA is a method of analyzing a system or component to obtain possible failure modes, effects, and causes [31]. Recommendations developed through the process of creating a FMECA may reduce failure risk to the system or component. FMECA results will contain a prioritized list of failure modes based on expected probability of occurrence and severity of impact.

In addition to the risk register as described above, a FMECA should be completed for all WPTO-funded MEC technology development projects at TRL 4 or higher and should comply with the requirements in IEC TS 62600-4 (technology qualification) [22] while using the methods from IEC 60812 (FMECA) [31].

Additional FMECA details for MEC applications are contained in Section 6. The cover page for this report contains a link to a FMECA template [32]. Appendix C contains references for FMECAs and other risk management tools.

4.6 Design Basis

The scope of the design basis document includes the entire MEC system, such as the primary MEC device, anchors, grid connections, energy storage, communication systems, and more. The design basis document is maintained throughout all technology development cycles, with the following subsections:

4.6.1 Design Basis—Requirements

The design basis requirements state the conditions the MEC technology must be designed to meet. These requirements may include environmental conditions, design standards, controllability, electric power quality/output, EHS requirements, and others. The design basis document should include requirements at each TRL development cycle.

The design basis should comply with the requirements within IEC standards, specifically, IEC TS 62600-2 (design requirements) [33]. The IEC Electropedia (also known as IEV Online) Part 417 provides definitions for all terminology in the IEC marine energy standards [14]. Using and complying with IEC standards will reduce negative risks for marine energy development as well as improve the commercial success for development projects.

Also, the design basis should consider the recommendations within European Marine Energy Centre's (EMEC's) design basis guidelines [34], the DNV service specifications for the certification of wave energy converters and arrays (DNV-SE-0120) [35], and the certification of tidal turbines and arrays (DNV-SE-0163) [36]. The WestWave Electricity Supply Board International's verification checklist may be helpful when developing TRL-specific requirements [37].

4.6.2 Design Basis—Loads

Design basis loads is a subset of the design basis document describing the load conditions the design must meet. These load conditions consider dead, live, and accidental load conditions during all relevant life phases (manufacturing, transportation, assembly, deployment, commissioning, normal operation, extreme events, faults, maintenance, and decommissioning). The same references stated in Section 4.6.1 apply to this loads document, as does IEC TS 62600-3, which provides a technical specification for the measurement of mechanical loads [38].

4.6.3 Design Basis—Design Description

The design description documents the design and should be adequate to build, integrate, and test the design. The design documentation may include model code, descriptive text, schematics, build prints, and/or an assembly design in the form of solid models or computer-aided design models.

At appropriate development phases, the design description documents for a deployment should also include plans for installation, decommissioning, and retrieval of the system. These deployment plans should include defined roles, contact information, statement of work, and an emergency management plan.

4.6.4 Design Basis—Design Analysis

The design analysis document presents analysis results for the design. These analyses are based on the requirements and loads from the design basis (Section 4.6.1 and 4.6.2). The analyses consider the structural response from load conditions and material resistance as appropriate. The analysis fidelity should be commensurate with failure risk.

4.6.5 Design Basis—Define Survivability, Reliability, and Maintainability Targets and Strategies

The MEC technology is expected to withstand the survivability targets, which may be a combination of environmental, operating, control, and fault conditions. The survivability strategy is the plan to achieve the survivability targets. These targets and strategies should be stated for each TRL and TPL development cycle.

Expected levels of reliability and maintainability for the MEC technology during a stated period are defined in the design basis document. Reliability targets should be defined in terms of mean time between failures or mean time to repair. Maintainability targets should be defined in terms of maintenance-free operating periods or maintenance recovery periods [39]. The reliability and maintainability strategy is the plan to achieve these targets.

The overall system may be broken down into subsystems when developing targets and strategies. Subsystems could be further broken down as necessary (similar to the FMECA system decomposition process shown in Section 6.1). The evaluation of targets and strategies at a subsystem (or lower) level may help inform decisions early on to optimize the strategy for the overall system.

These targets and strategies should comply with the requirements within Sections 6 and 12.9 of IEC TS 62600-2 [33]. The OES technology framework provides additional evaluation criteria and considerations for reliability, survivability, and maintainability of MECs [40]. The marine energy performance metrics from the PRIMRE Telesto database provide both performance and reliability metrics for the design basis [41]. Sections 6 and 8 from the EMEC reliability, maintainability, and survivability guidelines may be a useful reference when developing these targets and strategies [39].

4.6.6 Design Basis—Environmental, Health, and Safety

EHS aspects of the design basis must be considered throughout the technology development; the management of possible impacts from these aspects can be documented through a risk register or other means. The overall safety and environmental impacts from the MEC must be assessed and must be acceptable. The possible hazards from the MEC design should be comprehensively identified and appropriately managed. A safe-by-design workshop can help identify ways to integrate safety into the design, and past experiences with offshore wind energy may be relevant to marine energy [42]. Personnel entering a confined space within a MEC device is one of many possible hazards that require an appropriate strategy.

Specific EHS requirements will depend on local regulations and the institution doing the work. One recommendation is for a qualified EHS professional to be involved during the development and deployment of large and complex MEC devices [20].

4.7 Lessons Learned

Lessons learned (both good and bad) should be captured throughout the technology development process and at a formal debrief meeting following each TRL and TPL development cycle, per Figure 1. Section 7 contains details for collecting lessons learned.

5 Risk Register

Risk is defined as "*an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more objectives. Positive risks are opportunities, while negative risks are threats*" [16]. Managing risks is about managing everything uncertain that can impact the project objectives. The risk register is a tool to document the identification, analysis, and response planning for all forms of risk. A risk register may contain risks that are technical, nontechnical, project-based, or external, or that originate from any other source of uncertainty. A single risk register can include all known risks from all risk sources, or separate risk registers can be developed for each different identified risk source.

Potential system failure modes are technical risks that can be included in a risk register. However, a FMECA as described in Section 6 provides a better risk management tool for analyzing the cause and effects of failure risks for a MEC system. A risk register should consider the entire universe of uncertain events that can impact objectives, whereas a FMECA is a tool used specifically for analyzing failure risks, which is a subset of the risk register. A risk register and a FMECA are two different risk management tools that are best used together and not in place of each other.

The risk register is a repository for current risk information that could influence project success as described in the following subsections. Each risk is analyzed in terms of the severity of its impact to the project and the expected probability of its occurrence; the combination provides a basis for risk prioritization. The risk register contains a unique response plan describing how each risk will be managed. Monitoring and controlling risks involve detecting new risks and changes to existing risks. The ongoing process to monitor and control each risk should continuously occur throughout each technology development cycle displayed in Figure 1.

Figure 2 shows the risk register development processes along with the subsections that describe the processes in further detail. A risk register template is provided in the referenced spreadsheet [30], which uses consistent terminology with this framework document.

Figure 2. Risk register development processes

5.1 Identify Risks

The purpose of risk identification is to identify uncertainties that may impact the MEC technology development. These uncertainties may be from the application of a common design or from the pursuit of unproven design concepts. All uncertain project elements are possible inputs to the risk identification process. Identified risks should include both technical and nontechnical risks, with possible impacts to safety, cost, time, scope, quality, environment, or regulations. International standards may be used with or without adaptation to help identify risks. It is important to consider risks from other projects and industries that may be relevant to the MEC technology development.

Identified risks can be either positive (opportunities) or negative (threats). While risk management is often only considered for negative risks (threats), the same approach can be used to manage uncertainties that may have a beneficial impact on the project objectives (opportunities). Effective management of positive and negative risks is the best approach to achieve project objectives.

Risk identification involves categorically listing risks with associated risk owners. The process output is the creation and maintenance of a comprehensive risk registry. This registry will be continuously updated throughout the technology development project as new risks are identified or changes occur to existing risks. The following subsections describe the risk identification process.

Human error is an important risk to consider during all project phases. Careful consideration and management of possible human errors during commissioning, operating, and decommissioning a system can reduce the probability of these errors being significant.

5.1.1 Risk Breakdown Structure

The risk breakdown structure (RBS) is a hierarchical breakdown of all project risks into common categories. An RBS is useful for the comprehensive identification of risks.

The example RBS in Table 4 is purposefully broad to be a helpful starting point to develop a project-specific RBS. The RBS used in all projects should be provided with the risk register and should use the same RBS Level 1 categories provided in this example. The specific categories included in Level 2 of the RBS should be modified and customized to the risk profile of the particular project.

The RBS for safety risks is separated for internal (RBS 1.2) and external (RBS 1.3) personnel. External personnel are separated as an RBS level because external personnel may not have the same level of project knowledge as internal personnel.

Regulatory environmental risks for MECs would be mapped to RBS 5.6. The OES-Environmental *2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World* provides specific regulatory risks for MECs that would fit under RBS 5.6, such as collision risk, underwater noise, electromagnetic fields, changes in habitats, displacement/barrier effect, and changes in oceanographic systems (see Table 13.1 in [43]).

A cost breakdown structure (CBS)[2] for a MEC project is a hierarchical breakdown of all project costs into common categories. A CBS is useful for the complete identification and decomposition of cost and associated financial risk. The identified risks within the CBS may apply to multiple RBS levels in addition to being a useful guide for FMECA system decomposition (see Section 6.1) [44].

Table 4. Example Risk Breakdown Structure (RBS) [16] [45]

RBS Level 0	RBS Level 1	RBS Level 2
All sources of project risk	1. Safety Risk	1.1 All personnel
		1.2 Internal personnel
		1.3 External personnel
	2. Technical Risk	2.1 Scope definition
		2.2 Requirements definition
		2.3 Estimates, assumptions, constraints
		2.4 Technical processes
		2.5 Technology
		2.6 Technical interfaces
		2.7 System reliability
		2.8 Performance
		2.9 Security
		2.10 To be determined (TBD)
	3. Management Risk	3.1 Project management
		3.2 Program/portfolio management
		3.3 Operations management
		3.4 Organization
		3.5 Human resourcing
		3.6 Funding
		3.7 Communication
		3.8 Information
		3.9 Quality
		3.10 Reputation
		3.11 TBD
	4. Commercial Risk	4.1 Contractual terms and conditions
		4.2 Internal procurement
		4.3 Suppliers and vendors

[2] An example CBS worksheet for a MEC can be downloaded at https://mhkdr.openei.org/submissions/361 (see "MHK System Cost Breakdown Structure.xlsx") [44].

RBS Level 0	RBS Level 1	RBS Level 2
		4.4 Subcontracts
		4.5 Client/customer stability
		4.6 Partnerships and joint ventures
		4.7 Levelized cost of energy (LCOE)
		4.8 TBD
	5. External Risk	5.1 Legislation
		5.2 Exchange rates
		5.3 Site/facilities
		5.4 Environmental/weather
		5.5 Competition
		5.6 Regulatory
		5.7 Political
		5.8 Force majeure
		5.9 External stakeholder
		5.10 TBD

5.1.2 Technology Life Phases

Technology life phases are sequential stages of technology development that occur from concept to decommissioning. The life phases at a high level within each TRL and TPL cycle may include:

- Specification
- Design
- Procurement
- Manufacturing
- Transportation
- Assembly and commissioning
- Operation:
    - Normal power production
    - Extreme events
    - Faults
    - Maintenance
    - Repair
- Decommissioning.

Each TRL and TPL development cycle will have a set of technology life phases. When possible, the user should determine the appropriate technology life phases within each TRL and TPL development cycle, and assign risks to one, multiple, or all life phases.

Other technology development guidelines and metrics mentioned in Section 1 could be considered within the risk register (ARLs, CARAT, MRLs, etc.). These are optional for a MEC risk register, but the risk register could be modified to include these and other metrics.

5.1.3 Risk Owner

An owner is assigned to each risk within the risk registry with risk management responsibility throughout the project development cycle(s). Risk management responsibilities include monitoring and controlling the risks and implementing the risk response strategies. Monitoring risks includes noting any changes that may warrant an update to the risk registry. The risk owner should review the risk register at predetermined intervals in addition to adding new risks as they are identified.

5.2 Analyze Risks

Quantitative risk analysis is critical to the overall risk management plan. All risks should be characterized in terms of (1) classification with impact on safety, cost, time, scope, quality, environment, or regulation, (2) impact (e.g., severity or consequence), and (3) the probability or likelihood of occurrence. Based on the analysis, each risk can be prioritized and managed. The quantified risk priority may guide the team when making technology development decisions.

A probability and impact matrix [19] [16] is the tool described in this section (it is the same as a consequence/probability matrix [46]). This tool was chosen based on its ease of use and its application to a diverse set of project risk scenarios. A weakness of this tool is the subjective nature of assigning risk probability and impact levels [46]. The user is encouraged to use additional risk management tools that may be more appropriate for each unique situation.

The IEC/ISO 31010 standard describes many different tools and techniques to analyze risks, including consequence/probability matrix, fault tree analysis, scenario analysis, cost/benefit analysis, root cause analysis, and many others [46]. The PMI PMBOK Guide describes multiple risk analysis methods [19]; PMI's risk management standard provides even greater details on risk analysis tools and techniques [16].

5.2.1 Risk Classifications and Impact

Risk classifications (CLASS) are categorized by the areas primarily impacted by risk occurrence. These classifications, as shown in Table 5, include safety, cost, time, scope, quality, environment, and regulation. A risk impact value (IMPCT) is used to quantify the severity of the outcome should that risk occur. In Table 5, the risk increases in impact from 0 (no impact level), to 5 ("lethal"). The impact quantification combined with its probability of occurrence will enable risk prioritization.

The information in Table 5 is intended to be a starting point that is modified for each unique development project. A given risk could be assessed at every risk classification or at the perceived most important one(s), provided the impacts to the other risk types are maintained at acceptable levels when controlling the risk. For example, a given risk could be analyzed in terms of its impacts on safety and/or cost and/or time and/or other risk classifications.

Positive risks (opportunities) can be analyzed with opposite definitions of those in Table 5. For example:

- A “2 time opportunity” would advance—versus delay—the schedule by 1 week to 1 month.
- A “3 cost opportunity” would provide $350K of new funds instead of costing $350K.
- A “5 safety opportunity” would prevent a fatality versus resulting in a fatality.

Table 5. Example Risk Classifications and Impact Definitions [22]

Consequence with impact to persons, project, environment, and regulatory compliance								
Impact (IMPCT)	**Impact Level**	**Risk Classifications (CLASS)**						
		Safety (S)	**Cost (C)**	**Time (T)**	**Scope (P)**	**Quality (Q)**	**Environment (E)**	**Regulation (R)**
0	None	No injury	$0K	No delay	No scope impact	No quality impact	No pollution	Full compliance
1	Insignificant	Negligible injury, effect on health	$1.5K	Less than 1-week delay	Insignificant scope impact	Insignificant quality impact	Negligible pollution or no effect on environment	Insignificant regulatory infraction with no consequences
2	Marginal	Minor injuries, health effects	$15K	1-week to 1-month delay	Moderate scope impact	Moderate quality impact	Minor pollution/slight effect on environment (minimum disruption on marine life)	Moderate regulatory infraction with inconvenient but reversible consequences
3	Critical	Moderate injuries and/or health effects	$350K	1-month to 6-months delay	Major scope impact (rescoping required to some of the project)	Critical quality impact (possibly irreversible)	Limited levels of pollution, manageable/ moderate effect on environment	Major regulatory infraction causing system shutdown until compliance is reassured
4	Catastrophic	Significant injuries	$2.5M	6-months to 1-year delay	Serious scope impact (rescope most of project)	Catastrophic quality impact (likely irreversible)	Moderate pollution, with some cleanup costs/serious effect on environment	Serious regulatory infraction likely causing irreversible system shutdown and substantial fines
5	Lethal	A fatality	$13M	1-year or more delay	Complete scope impact (rescope entire project)	Devastating and irreversible quality impact	Major pollution event, with significant cleanup costs/ disastrous effects on the environment	Very serious regulatory infraction causing project shutdown, major fines and/or bankruptcy, lengthy legal proceedings

5.2.2 Risk Probability

The probability (PROB) value quantifies the probability of a risk occurring during a 1-year period. Risk probability is synonymous with risk likelihood or risk frequency. Table 6 contains definitions from IEC TS 62600-4 for a relative probability scale from 0 to 5 [22]; although these definitions are based on annual failure rate (AFR), "failure" can also be considered the "occurrence" of the risk for non-failure-type risks. Typically, the assigned probability is based on the expert judgment of the user in combination with historical data when available. Also, published reliability data from similar industries such as offshore oil and gas should be considered as appropriate [47].

Table 6. Risk Probability Definitions [22]

Probability (PROB)	Probability Description	AFR (% per year, up to)	Frequency of Occurrence (up to)
0	Not Possible	0%	Never
1	Very Low	0.01%	Once every 10,000 years
2	Low	0.1%	Once every 1,000 years
3	Medium	1%	Once every 100 years
4	High	10%	Once every 10 years
5	Very High	100%	Once a year

AFR = (F/(U × T) ×100, where [48]:

- **AFR** is the annual failure rate (%)
- **F** is the number of failures
- **U** is the number of units tested
- **T** is the time period over which the units were tested (years).

5.2.3 Risk Priority Number

The risk priority number (RPN) is derived from a probability and impact matrix, and it provides a measure of risk priority. The RPN is the product of the risk probability and impact values. The RPN is segregated into low-, medium-, and high-risk zones, as shown in Figure 3, with the categories defined from IEC TS 62600-4 [22]. The RPN matrix is not symmetrical; a very high-probability risk (5) with a very low impact (1) has low-priority RPN (5), while a very low-probability risk (1) with very high impact (5) has a medium-priority RPN (5). The reason that both scenarios result in an RPN of 5 but have different priorities is that more uncertainty is expected in the probability assessment than the impact assessment; therefore, it is better to be conservative for a very-high-impact risk with an uncertain very-low-probability assessment.

Generally, a low RPN should be targeted for all negative risks, a medium RPN may be acceptable under certain circumstances, and a high RPN is unacceptable. The user should define project-specific acceptability thresholds.

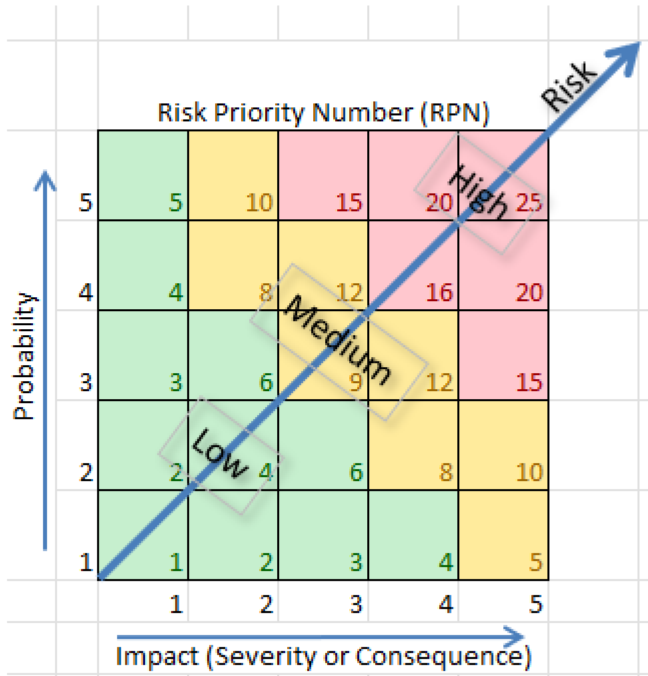

Figure 3. Risk priority number [22]

5.3 Plan and Execute Risk Responses

A risk response plan describes how each unique risk will be managed. A risk response plan is important because each risk may have interdependencies with other project functions. The implications of each risk occurring is considered when developing the response plan. The risk register is structured to contain information described in the following subsections for each identified risk.

5.3.1 Risk Response Strategies

The risk response strategy describes the type of response to each risk. The response strategy for each risk is structured using the strategy types in Table 7 combined with a unique description. An effective response strategy requires budget and schedule authorization to implement the response for each risk. The response may address the root cause and/or the effect of the risk and should consider input from—and be communicated to—all relevant project stakeholders [16].

The five strategy types for negative risk (threats) responses are avoid, transfer, mitigate, accept, and escalate (Table 7). The avoid strategy is usually preferred for negative risks because if avoided, the risk will not impact the project. The transfer strategy may be used if an important risk cannot be avoided or mitigated and there is a third party willing to accept the risk. Likely the most common strategy, the mitigate strategy aims to reduce the probability and/or impact of the risk. An accept strategy may be chosen because the risk impacts are negligible and no actions are needed, or because there are no reasonable options for a risk response. Alternatively, the accept strategy may be conditional if a process is started under controlled conditions to verify risk assumptions, or it may be temporary if data are obtained under controlled conditions for future risk reassessment. The escalate strategy may be chosen when the risk response needs to come from a higher level within the organization.

The positive risk (opportunity) response strategies are complementary to the associated negative strategies (Table 7). Positive risk response strategies aim to maximize impact from uncertain opportunities.

Table 7. Risk Response Strategies [16]

Negative Risk (Threats) Responses		**Positive Risk (Opportunity) Responses**	
Strategy Type	**Strategy Description**	**Strategy Type**	**Strategy Description**
Avoid	Ensuring the risk cannot occur or will have no impact on the project (e.g., removing high-risk equipment from the system)	Exploit	Ensuring the opportunity will occur and the project will benefit from it
Transfer	Transferring the risk to a third party (e.g., insurance company)	Share	Sharing the opportunity with another party
Mitigate	Reducing the probability and/or consequence of a risk	Enhance	Increasing the probability and/or consequence of an opportunity
Accept	Accepting the risk without pursuing any of the other strategies—contingency plans may be developed if the risk occurs	Accept	Accepting the opportunity without pursuing any of the other strategies
Escalate	Escalating the risk response to the level within the organization that can provide an appropriate response	Escalate	Escalating the risk response to the level within the organization that can provide an appropriate response

5.3.2 Risk Response Timing or Triggers

The timing or trigger conditions clearly identify *when* a risk response commences. Timing may simply be a schedule for implementing the risk response (e.g., risk response strategy will be implemented on June 24). Alternatively, the risk response may be triggered by conditions—other than the risk becoming reality (e.g., implement response if project is over budget by more than 10% at any quarterly review).

5.3.3 Residual Risk After Risk Response

The residual risk quantifies the expected results from the risk response, which includes the residual risk RPN and a description of the anticipated results. The residual risk RPN is calculated using the same methods as the baseline risk (see Section 5.2). The residual risk description includes the expected primary outcome from the risk response (i.e., the expected results by implementing the response strategy).

From Table 7, for an avoid strategy, the residual risk probability and/or impact is zero. For a transfer strategy, the residual risk impact may be less because a third party is sharing responsibility, but the probability will remain unchanged. For a mitigate strategy, the residual risk probability and/or impact will be less. For an accept strategy, the residual risk probability and impact will be the same as the baseline risk condition.

5.3.4 Secondary Risks Resulting From Risk Response

Secondary risks are those risks *caused* by implementing a risk response strategy to the primary risk. It is important to identify and analyze secondary risks to ensure the risk response is worth pursuing. The risk register includes a field identifying secondary risks within each primary risk; each secondary risk is analyzed as a separate risk item within the risk register using the Section 5.2 methods, as appropriate.

5.4 Monitor and Control Risks

Monitoring and controlling risks is a process that occurs continuously throughout each technology development cycle (Figure 1). Monitoring risks includes (1) detecting any differences between the current project conditions and the risk register information and (2) identifying new risks not contained within the risk register. Controlling risks includes the execution of risk responses by the risk owner according to the risk response timing and trigger conditions. The risk register is updated with the status and new information according to the cycle in Figure 2.

5.4.1 Risk Triggers

Risk triggers are situations or events that *may* lead to the risk occurring. Monitoring and controlling risks include noting if any trigger conditions have or may be about to occur.

5.4.2 Contingency Plan

The contingency plan describes the actions to take if a risk event occurs—when the risk response strategy was not successful in preventing the negative risk event from occurring (or conversely, it was successful in realizing the positive risk event). Each risk within the risk register contains a unique contingency plan.

For example, there may be an estimated 5% probability that a critical regulatory permit will not be issued for a project. The *contingency plan* lists the action to be taken if this permit is not issued. In contrast, the *risk response strategy* may be the actions that minimize the probability or impact of the permit not being issued.

5.4.3 Risk Status

The risk status is simply the status of the risk and management plan on a stated date. The risk status could be active monitoring pending the completed risk response, active monitoring with a completed risk response, or possibly the risk has occurred with the contingency plan soon to be implemented. If a risk trigger event occurred but the risk has not yet occurred, then the status may be given a priority because the risk may be imminent. If a risk is no longer relevant and cannot occur in the future, either because the risk has already occurred or it cannot occur, then the risk may be retired.

5.4.4 Recommendations and Action Items

Recommendations and action items are the specific tasks to be completed by the risk owner for the management of the risk. Implementing risk responses and monitoring for risk triggers is a typical action item, but other unique recommendations are possible for each risk.

6 Failure Modes, Effects, and Criticality Analysis

A FMECA for a MEC system provides a way to assess failure modes, failure effects, and potential failure causes and to develop recommendations to mitigate or manage these failures. A benefit of completing a comprehensive FMECA is possibly preventing failures from occurring. A FMECA can also improve overall system reliability and lower cost. The IEC 60812 standard provides extensive details on all aspects of developing and following a FMECA process [31]. A core part of marine energy technology qualification through IEC TS 62600-4 is through FMECA methods [22].

Human error is a common cause of many different failure modes that should be carefully considered throughout the FMECA process. A well-developed FMECA will identify ways to prevent human errors from occurring, which will reduce the impacts of these errors on the MEC system.

A FMECA is a subset of a failure modes effects analysis (FMEA). The addition of a "criticality" assessment to an FMEA allows failure modes to be prioritized. Sometimes FMECAs are referred to as FMEAs, but if the failure modes are being prioritized based on a criticality assessment, then FMECA is the more precise term.

6.1 FMECA Process

The overall process to complete a FMECA is shown in Figure 4, which is reproduced with IEC permission from IEC 60812 [31]. This process was used to develop a FMECA Excel template for MEC applications, which is part of this risk framework document [32].

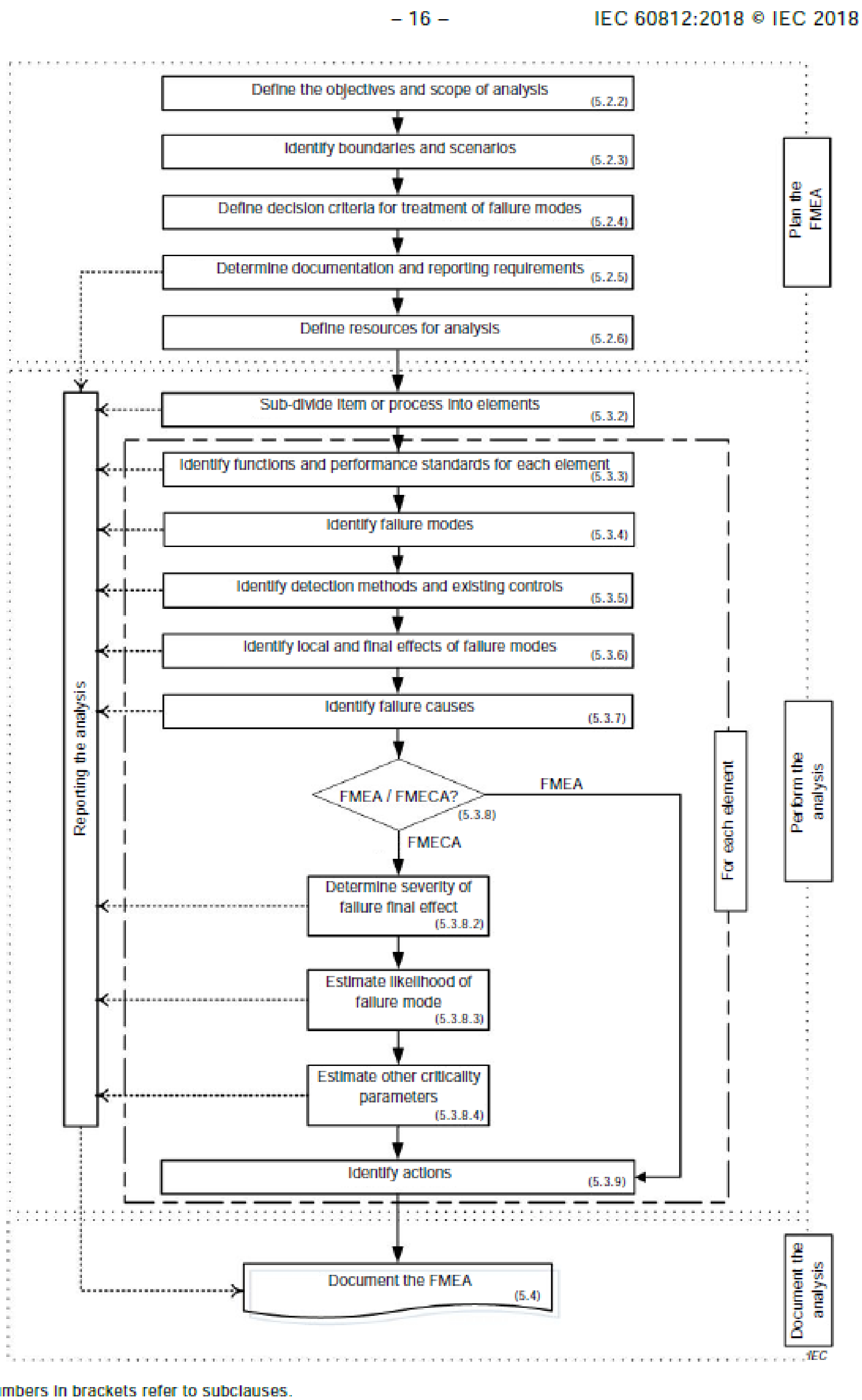

Figure 4. Overview of FMEA/FMECA process from Figure 1 of IEC 60812 ed. 3.0 [31][3]

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The following six steps outline the process to plan and complete a FMECA with section references to IEC 60812 [31], and column references to the FMECA Excel template for MEC applications [32].

1. Plan FMECA:
    a. Define the **objectives** and **scope** for the FMECA, which should state the purpose for the analysis and define the system to be analyzed (Section 5.2.2 in [31]).
    b. Identify the **system boundaries** and **scenarios** to be analyzed. The system boundaries should clearly state what is in/out of scope for the FMECA. The scenarios to be analyzed may consider different system life phases such as manufacturing, installation, normal operation, operation during a fault condition, extreme events, maintenance, repairs, decommissioning, retrieval after a failure, and others (Section 5.2.3 in [31]).
    c. Define the **decision criteria** for the FMECA. The FMECA template [32] currently uses information from IEC TS 62600-4 (Tables A.1, A.2, and A.3 in [22]) for this decision criteria, which requires no additional definitions unless changes are necessary (Section 5.2.4 in [31]).
    d. Determine **documentation** and **reporting** requirements, which should answer how the FMECA results will be reported. A FMECA could be reported with a prioritized list of the top failure modes with recommended actions, or the FMECA information can be reported in other ways (Section 5.2.5 in [31]).
    e. Define **resources** for analysis. A comprehensive FMECA may take significant time to be done effectively, which requires planning and allocating adequate resources for the effort (Section 5.2.6 in [31]).
2. Decompose system into elements (Section 5.3.2 in [31]) (**FMECA template columns B–E** [32]). Decompose the system into subsystems, assemblies, subassemblies, and components. Additional system decomposition fields can be added if necessary by adding new columns to the FMECA template between columns E and F [32]. Not everything in the system will be decomposed into components; in some situations, assemblies and subassemblies may be the lowest level for system decomposition.

    While the FMECA template is developed for system decomposition of a WEC design, this same template can also be used for processes that are broken into a sequence of steps. If processes are being analyzed in the FMECA, then the fields from columns B–E may be renamed to align with the decomposed process. The other fields in the existing system design FMECA template can be used without modification for a process FMECA.

    It is important to finish the comprehensive system decomposition before beginning the failure analysis for each element.

    a. See Figure 5 for a sample view of a general system hierarchy decomposed into subsystems, assemblies, subassemblies, and components.

   b. See Figure 6 for a sample view of an example WEC system decomposed into elements.
   c. A marine CBS (available for download from [44]) may provide a useful guide to decompose a marine energy conversion system into FMECA elements. (Note: an example CBS is shown in **FMECA template rows 5–85** [32].)

3. Define the function and performance standard for each element (Section 5.3.3 in [31]) (**FMECA template column F** [32]).
4. Complete the failure analysis for each element (**FMECA template columns G–V** [32]). Each row is a unique failure mode analysis for an element. Each element may have more than one row for failure mode analyses.
5. Add any notes that did not apply to other fields into the notes field (**FMECA template column W** [32]). If desired, add an index or risk identifier into the ID field (**FMECA template column A** [32]).
6. Document the FMECA (Section 5.4 in [31]) based on the plan from Step 1d (Section 5.2.5 in [31]).

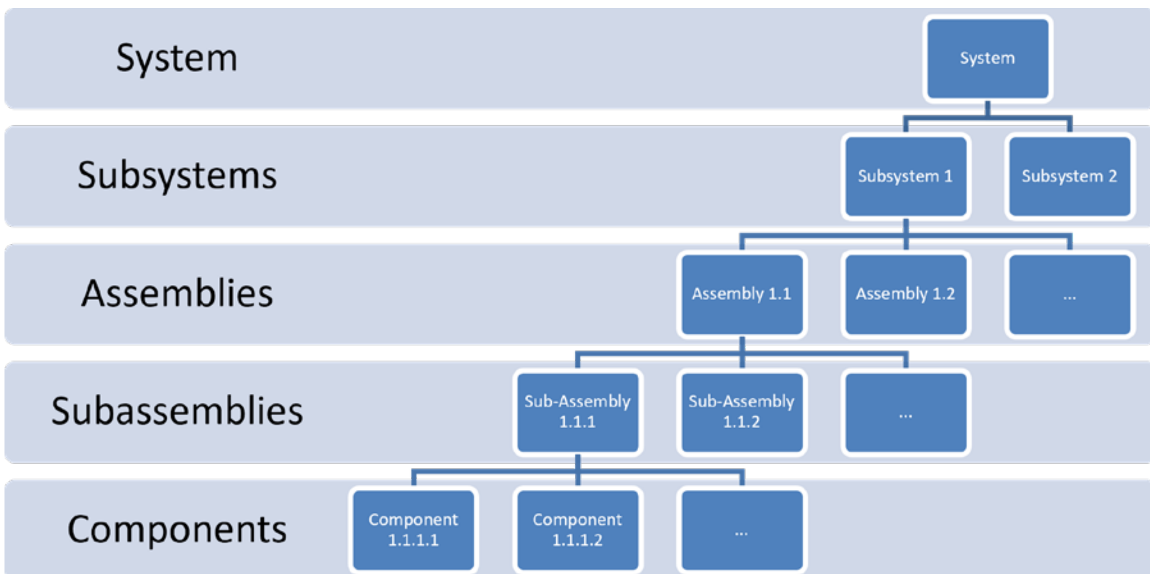

Figure 5. Example general FMECA system hierarchy decomposed into subsystems, assemblies, subassemblies, and components

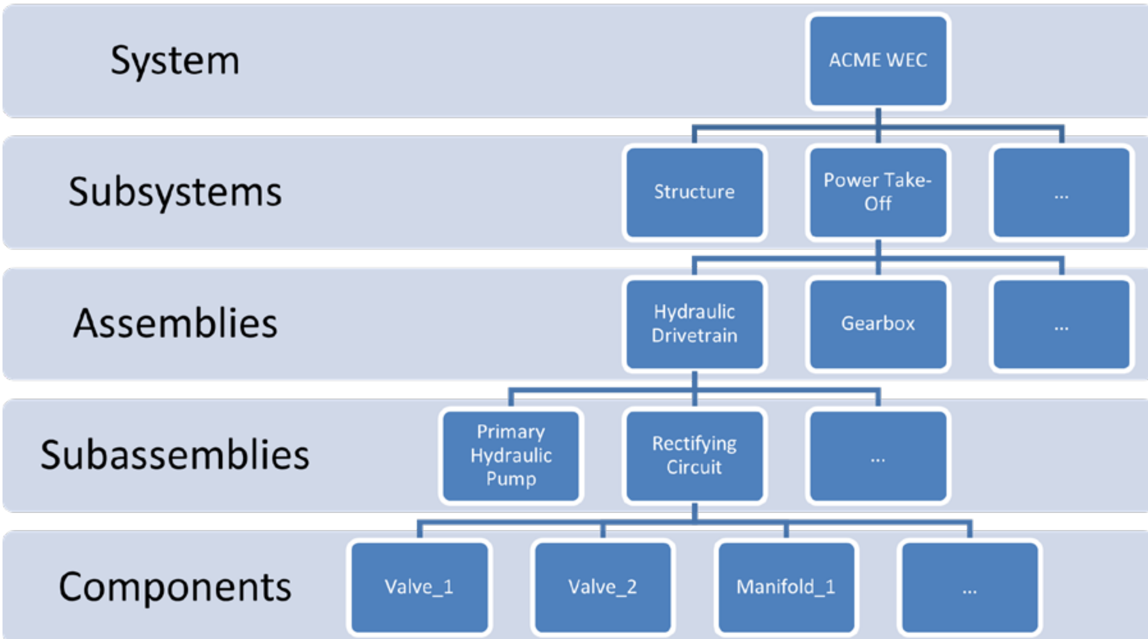

Figure 6. Example MEC FMECA system hierarchy decomposed into subsystems, assemblies, subassemblies, and components

6.2 FMECA Criticality Assessment

The criticality assessment for a MEC FMECA shall be based on the IEC TS 62600-4 standard; Tables 8–10 are reproduced with IEC permission from this standard:

Table 8. Probability of Occurrence for MEC FMECA (Reproduced Table A.1 From IEC TS 62600-4:2020 [22][4])

Class	Name	Description	Indicative Annual Failure Rate (Up To)
1	Very low	Negligible event frequency	1.0E-04
2	Low	Event unlikely to occur	1.0E-03
3	Medium	Event rarely expected to occur	1.0E-02
4	High	One or several events expected to occur during the lifetime	1.0E-01
5	Very High	One or several events expected to occur each year	1.0E+00

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Table 9. Classification of Impact for MEC FMECA (Reproduced Table A.2 From IEC TS 62600-4 [22][5])

Description of Consequences (Impact On)					
Class	**Safety**	**Environment**	**Operation**	**Assets**	**Cost (USD)**
1	Negligible injury, effect on health	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1.5K
2	Minor injuries, health effects	Minor pollution/slight effect on environment (minimum disruption on marine life)	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	15K
3	Moderate injuries and/or health effects	Limited levels of pollution, manageable/moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	350K
4	Significant injuries	Moderate pollution, with some cleanup costs/serious effect on environment	Total loss of production up to 2.5M (USD)	Significant but repairable outside maintenance interval	2.5M
5	A fatality	Major pollution event, with significant cleanup costs/disastrous effect on the environment	Total loss of production greater than 2.5M (USD)	Loss of device, major repair needed by removal of device and exchange of major components	13M

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Table 10. Risk Priority Matrix for MEC FMECA (Reproduced Table A.3 From IEC TS 62600-4 [22][6])

Consequence					
Probability	**1**	**2**	**3**	**4**	**5**
5	Low	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med
Low	Tolerable, no action required				
Medium	Mitigation and improvement required to reduce risk to low				
High	Not acceptable: mitigation and improvement required to reduce risk to low (ALARP)				

6.3 FMECA Template Instructions

Table 11 contains a description for each column within the MEC FMECA Excel template [32]. An important definition is for *element*, which is the decomposed system item that is being considered for the failure mode analysis and which is typically the *component* but could be a higher-level decomposed system item.

Table 11. Column Name, Descriptions, and References From MEC FMECA Excel Template [32]

Column	Name	Description	Reference
A	Risk Identification or Index	This field provides a unique identifier for each row. This field may be populated with incrementally increasing numbers after the FMECA is nearing completion, but then adding a new row within the table would require reordering these IDs or adding nonsequential numbers as the new ID. Other options for this field include assigning a random number as the ID or developing a user-defined alphanumeric ID. The ID could be a numeric convention related to the system decomposition (e.g., 100.1.1.1.1, 100.1.1.1.2, …).	
B	Subsystem	This is the highest level of the system decomposition. The overall MEC system is made up of the sum of all the subsystems.	
C	Assembly	Each subsystem may be decomposed into one or more assemblies.	

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Column	Name	Description	Reference
D	Subassembly	Each assembly may be decomposed into one or more subassemblies.	
E	Component	Each subassembly may be decomposed into one or more components. Components are the lowest level of the system decomposition. If lower levels are necessary, then new column(s) may be added between E and F.	
F	Function & Performance Standard	The specific function of the decomposed element toward the purpose of the overall system. The performance standard(s) for this element states how its functional performance is qualified, which may include standards.	Section 5.3.3 from IEC 60812 [31]
G	Potential Failure Mode	The potential failure mode for the element. The element has failed when it does not meet its function and performance standard. Failure modes may be identified through experience, expert knowledge, external references, or brainstorming methods. Additional rows should be used to analyze each unique failure mode for the same element.	Section 5.3.4 from IEC 60812 [31]
H	Detection Methods	The method(s) (if any) to detect the failure mode for the existing system. Detection methods may reduce the failure mode severity.	Section 5.3.5 from IEC 60812 [31]
I	Local Effect	The local effect of the failure on the element. For example, the local effect could be the element fails to perform its stated function, or possibly the element has a change in performance.	Section 5.3.6 from IEC 60812 [31]
J	Final Effect	The final effect of the failure on the overall system. The final effect considers how a local failure may lead to a different (usually greater) failure to the overall system. For example, the “local effect” from a worn seal may be water ingress into a chamber, while the “final effect” of this failure could be the MEC sinks.	Section 5.3.6 from IEC 60812 [31]
K	Classification	The classification of failure consequence in terms of safety, environment, operation, assets, or cost. Choose the most relevant classification when multiple classifications are relevant to a failure mode, unless the analysis and response may be different for each classification, in which case each classification should be evaluated on different rows.	Table 9
L	Severity	The severity of the failure; 0 to 5 rating with severity increasing with larger values.	Table 9 and Section 5.3.8.2 from IEC 60812 [31]

Column	Name	Description	Reference
M	Potential Failure Cause	The potential cause of the failure mode. Consider all potential failure causes such as overload events, long-term fatigue, wear, interference, design errors, manufactured defects, corrosion, biofouling, external factors, human error, and many other causes. Use more than one row to analyze a single failure mode that may have multiple potential causes with different probabilities and recommended actions.	Section 5.3.7 from IEC 60812 [31]
N	Prevention Controls	The existing controls that may prevent the failure from occurring.	
O	Probability	The probability of occurrence for the failure (also known as the likelihood of failure); 0 to 5 rating with probability increasing with larger values.	Table 8 and Section 5.3.8.3 from IEC 60812 [31]
P	Risk Priority Number (RPN)	The RPN is calculated by multiplying the failure severity by its probability. This is the baseline RPN for the existing system before any efforts may be taken to lower it through recommended actions. • A Low RPN is usually tolerable with no additional action required. • A Medium RPN should have actions identified to lower the RPN if possible. • A High RPN is not acceptable, and actions should be identified to reduce the risk as low as reasonably practicable.	Table 10
Q	Recommended Action(s)	The list of recommendations to take that are expected to lower the severity and/or probability of a failure mode.	Section 5.3.9 from IEC 60812 [31]
R	Actions Taken	The actual actions taken after the baseline risk analysis, which will become a compiled list of actions when more than a single round of risk mitigation is completed.	
S	Action Results: Severity	The failure mode severity after implementing the stated “actions taken,” which should result in equal or lower severity from the baseline severity.	
T	Action Results: Probability	The failure mode probability after implementing the stated “actions taken,” which should result in equal or lower probability from the baseline probability.	
U	Action Results: Risk Priority Number (RPN)	The calculated RPN from implementing the recommended actions.	
V	Contingency Plan	The planned actions to take if the failure mode occurs.	
W	Notes	Any notes pertaining to the failure mode analysis that do not fit within other fields.	

6.4 FMECA Data Sources

The analysis data for FMECA will often come from estimates based on experience, but data from external sources should be used when available.

6.4.1 Mooring Failure Data

The following sources may provide useful information when identifying and analyzing mooring failure modes:

- Annual probability of mooring failure estimated at 0.3% for the conditions stated in this reference: https://ccom.unh.edu/seminars/challenges-mooring-system-design-floating-offshore-installations.
- Failure modes for mooring lines include wear, fatigue damage, abrasion, corrosion, damage, flawed materials, and excessive tension: https://acteon.com/blog/seven-mechanisms-that-contribute-to-mooring-line-failure/.
- Failure of unrated mooring buoy resulting in $4.5M damages: https://www.iims.org.uk/mooring-buoy-failure-caused-grounding-causing-damage-of-4-5m-reveals-ntsb-report/.
- Hydrogen embrittlement is most common failure mode for high-strength mooring chains: https://www.offshore-mag.com/business-briefs/equipment-engineering/article/14287387/dnv-investigates-mooring-lines-failures.
- BP assessment of mooring failure rates and contributing factors: https://mcedd.com/wp-content/uploads/2014/04/00_Guy-Drori-BP.pdf.
- Accident investigation of mooring failure: https://www.imca-int.com/safety-events/failure-of-moorings-during-heavy-weather/.

6.4.2 Learnings From Other Industries

Every FMECA will be unique to the analyzed MEC technology. However, lessons learned from other industries may help mitigate MEC failures. The following are a small sample of such lessons learned:

- Reliability data for offshore and onshore oil and gas [47]: https://oreda.com/.
- Diesel generator failure leading to vessel fire: https://www.ntsb.gov/news/press-releases/Pages/NR20211215.aspx.
- Power outage could have resulted in catastrophic failure: https://www.upstreamonline.com/safety/power-outage-could-have-led-to-catastrophic-failure-at-shell-s-prelude-flng-facility/2-1-1139413.

7 Lessons Learned

Collecting lessons learned is an important part of a comprehensive risk management plan because it promotes organizational learning that may reduce the probability and/or impact of future negative risks (threats), and it may improve the probability and/or impact of future positive risks (opportunities). The lessons learned provide input to improve the risk management plan (Section 4.1) as shown in Figure 1. Also, it may help foster future successes in areas where positive outcomes were realized.

Lessons learned may be documented using separate tables: one for issues (problems) and one for successes. The issue table should describe each issue along with its impact and contain recommendations for improvement. The success table should describe each success, factors supporting the success, and the impact of the success. Action items are assigned to implement changes based on each lesson learned.

Lessons learned are best captured when they are noted by a team member. A formal debrief meeting with all team members should conclude each technology development cycle. The debrief meeting allows the team to stop and examine what occurred during the previous development cycle. The risk register is updated, as appropriate, with information from lessons learned.

Any incident occurring during the development or deployment cycle should be documented. Incidents may include adverse events, near misses, hazardous conditions, security breaches, or equipment malfunctions [49]. The internal and external reporting process of incidents will depend on the organization and be connected to the lessons learned log. The following are suggested steps for documenting incidents:

- What happened (including timeline) during the incident (who, what, when, where, why)?
- What should have happened to avoid the incident?
- Corrective action plan (with estimated completion dates).
- Lessons learned (Table 12).

Some lessons learned may have root cause(s) that will require a root cause analysis to understand. A FMECA is one tool for a root cause analysis, but there are many more methods. The "5 Whys Analysis" is a simple but powerful technique to determine the root cause of an issue by asking "Why" five times to get to the root cause of an issue. Understanding the root cause of a lesson learned may help to prevent it or something similar from reoccurring by understanding the original decision that led to the issue [50].

Any component or system failure during a development or deployment phase should be documented when it occurs and be discussed during a lessons learned meeting. Important failure attributes to document include the timing for the failure, hours of normal operation leading up to the failure, the failure mode, events leading up to the failure, detectability of the failure, potential failure causes, and effects of the failure. The data of interest from an actual failure are similar to the fields within the FMECA, which can result in data to inform the criticality assessments for a future FMECA to help prevent the failure from reoccurring.

It is important to consider how and when a lesson learned is escalated within an organization. Similar to how "Escalate" is one possible risk response strategy (Table 7), there may come a time when a lessons learned should be escalated. The development of escalation thresholds is recommended, along with corresponding actions that are based on the risk tolerance for the organization. These escalation thresholds could be based on financial impact or other important factors to the organization. Codifying these thresholds before they are needed will help ensure efficient information flow within an organization.

It is important to share some lessons learned with the broader MEC industry. Sharing lessons learned—particularly related to safety—will foster overall success for the industry without compromising competitiveness.

The following are suggested templates for documenting lessons learned during or after each development cycle. Table 12 is a suggested template to document issues, and Table 13 is a suggested template to document successes. Mock data are shown in these tables to demonstrate their potential use; red font is used to highlight action items. The Vanderbilt Guide contains additional recommendations for collecting lessons learned through an after-action review [51].

The following are some possible questions to consider when conducting a project debrief:

- What worked well—or did not work well—during this development cycle?
- What worked well—or did not work well—for the project team?
- What needs to be done differently?
- What project circumstances were not anticipated?
- How can we improve our technology development process?

Table 12. Template for Lessons Learned Issues (Mock Data Shown)

Date	Project Cycle	Issue Category	Issue Name	Issue Description (Possible Cause)	Impact	Recommendation for Improvement (Action Items)	Action Item Initials	Action Item Due Date	Follow-Up Actions Completed
240112	TRL 5, TPL 7	Scope	Bolt torque	It was uncertain if bolts on generator were torqued according to the specification	Potential damage to generator if operated without proper torque; required potentially unnecessary retorque operation	Develop a checklist for technician to initial when torque operation completed	MD	240212	Checklist developed for next test phase
240112	TRL 5, TPL 7	Quality	Missing test records	During testing, notes were not regularly taken by test personnel	Unable to reconstruct the actual test events	Develop a dedicated logbook for each test campaign; develop process for capturing test events in logbook	RB	240412	Logbooks available for each test; procedure developed for logbook usage
240112	TRL 5, TPL 7	Human resource	Staff availability	Staff availability was unknown in advance of absence	Testing was delayed due to key staff being unavailable	Develop a staff calendar indicating upcoming staff vacations and other out-of-office events	DS	240312	TBD

Table 13. Template for Lessons Learned Successes (Mock Data Shown)

Date	Project Cycle	Success Category	Success Name	Success Description	Impact	Factors Supporting Success (Action Items)	Action Item Initials	Action Item Due Date	Follow-Up Actions Completed
240112	TRL 5, TPL 7	Integration	Good test setup	All test setup components functioned as expected	No mid-test rework	Good test setup planning; develop test plan template from existing test phase	TJ	240312	TBD
240112	TRL 5, TPL 7	Safety	No injuries	No injuries occurred during test project	Healthy team; satisfied management expectations	Team's commitment to safety; safe operating procedures; check if any gaps may exist between existing safe operating procedures and scope of next test phase	JJ	240119	Existing SOP adequately covers scope of next project phase
240112	TRL 5, TPL 7	Quality	Test setup mainten-ance	Thorough daily test maintenance during test phase addressed issues before major problems developed	Potential major problems avoided	Diligent technicians and relevant checklists; add maintenance checklist requirement for next pre-test review	BE	240212	Maintenance checklist added to requirements for next pre-test review

7.1 Definitions for Terms Used Within the Fields From Table 12 and Table 13

Date—the date when the problem/success was documented.

Project Cycle—the project cycle based on TRL and TPL designations from Figure 1.

Issue/Success Category—the category assigned for each problem/success. The seven risk type categories from Table 5 may be used to categorize the lessons learned in addition to other project function categories. Although each issue/success may fit within more than one category, choose one category with the greatest impact.

Issue/Success Name—the unique name given to the identified issue/success.

Issue Description (Possible Cause)—the description of the issue along with any possible causes.

Success Description—the description of the success.

Impact—the impact on the project or team as a result of the specific issue/success.

Recommendation for Improvement (Action Items)— recommendations that may reduce the probability of reoccurrence or impact of the issue. Action items should be listed to implement these changes. Action items are shown in red font within Table 12 to highlight items requiring follow-up.

Factors Supporting Success (Action Items)—the positive factors that contributed toward the successful outcome. Action items should be listed if activities can be implemented that promote these factors to reoccur in the future. Action items are shown in red font within Table 13 to highlight items requiring follow-up.

Action Item Initials—the person responsible for executing the action item.

Action Item Due Date—the date when the action item is due.

Follow-up Actions Completed—the follow-up actions taken based on the assigned action items.

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Appendix A. Risk Management Outlined Bibliography (Standards, Guides, and Reports)

The following is an outlined bibliography for further reading on topics related to MEC risk management. The underlined text contains external links to the source document. The information presented here is not listed in any particular order.

A.1 Terminology

The IEC Electropedia (also called IEV Online) Part 417 provides definitions to all terminology in the IEC marine energy standards [14]; Part 417 has replaced IEC TS 62600-1 [15]

ISO 31072:2022, Risk management vocabulary [52]

A.2 Certification and Qualification Guidelines

IEC 62600 Marine energy suite of standards from TC114 [13]

IEC/TC114 Marine Energy Standards Cheat Sheet [53]

IECRE certification system for IEC renewable energy standards [24]

Llyod's Register Guidance Notes for Certification Through Technology Qualification [23]

ABS Technology Qualification [54], cutsheet [55]

Bureau Veritas Certification Scheme for Marine Renewable Energy Technologies [56]

DNV-RP-A203, Technology Qualification [25]

DNV-SE-0120 Certification of Wave Energy Converters and Arrays [35]

DNV-SE-0163 Certification of Tidal Turbines and Arrays [36]

A.3 General and Marine Risk Management

PMI's PMBOK Guide, 7th edition [19]

PMI's Standard for Risk Management in Portfolios, Programs, and Projects [16]

ISO 31000 Risk Management Guideline [17]

ISO 31000:2018 - Risk Management, A Practical Guide [18]

IEC/ISO 31010 Risk Management Techniques [46]

DNV-RP-N101 Risk Management in Marine Operations [57]

ABS Offshore Risk Assessment [58]

API 17N Subsea Risk Management [59]

Practical Project Risk Management with ATOM Methodology [45]

Marine Risk Assessment, Offshore Technology Report, DNV—2001/063 [60]

A.4 Failure Management

IEC 60812, FMEA Analysis Techniques [31]

DNV-RP-D102, FMEA of Redundant Systems [61]

IMCA M166, Guidance on FMEA [62]

Failure Mode and Effects Analysis Book Section [63]

IEC 61025, Fault Tree Analysis [64]

SIST EN 61078: 2017, Reliability Block Diagram [65]

SIST EN 62502:2011, Event Tree Analysis Techniques [66]

A.5 Design and Testing Guidelines

IEC 62600 Marine energy suite of standards from TC114 [13], including:

- IEC TS 62600-2, Marine energy – Wave, tidal and other water current converters, Part 2: Marine energy systems – Design requirements [33]
- IEC TS 62600-3, Marine energy – Wave, tidal and other water current converters, Part 3: Measurement of mechanical loads [38]
- IEC TS 62600-4, Marine energy – Wave, tidal and other water current converters, Part 4: Specification for establishing qualification of new technology [22]
- IEC TS 62600-10, Marine energy – Wave, tidal and other water current converters, Part 10: Assessment of mooring system for marine energy converters (MECs) [67]
- IEC TS 62600-20, Marine energy – Wave, tidal and other water current converters, Part 20: Design and analysis of an Ocean Thermal Energy Conversion (OTEC) plant – General guidance [68]
- IEC TS 62600-30, Marine energy – Wave, tidal and other water current converters, Part 30: Electrical power quality requirements [69]
- IEC TS 62600-40, Marine energy – Wave, tidal and other water current converters, Part 40: Acoustic characterization of marine energy converters [70]
- IEC TS 62600-100, Marine energy – Wave, tidal and other water current converters, Part 100: Electricity producing wave energy converters – Power performance assessment [71]
- IEC TS 62600-102, Marine energy – Wave, tidal and other water current converters, Part 102: Wave energy converter power performance assessment at a second location using measured assessment data [72]
- IEC TS 62600-103, Marine energy – Wave, tidal and other water current converters, Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-protype devices [6]
- IEC TS 62600-200, Marine energy – Wave, tidal and other water current converters, Part 200: Electricity producing wave energy converters – Power performance assessment [73]

- IEC TS 62600-202, Marine energy – Wave, tidal and other water current converters, Part 202: Early stage development of tidal energy converters – Best practices and recommended procedures for the testing of pre-prototype scale devices [7]
- IEC TS 62600-300, Marine energy – Wave, tidal and other water current converters, Part 300: Electricity producing river energy converters – Power performance assessment [74].

EMEC design basis guideline [34]

EMEC reliability, maintainability, and survivability guideline [39];
Annex F defines risk in terms of equipment maturity and organizational capability

OES Guideline by Holmes, for testing wave energy systems [28]—provides a test validation outline based on technology TRL

EquiMar Protocols for assessing marine energy converters [26]

DNV-ST-C501 Composite Components [75]

International Towing Tank Conference Guideline for model test experiments [27]

ABS Guide for Fatigue Assessment Of Offshore Structures [76]

DNV-OS-C101 Structural Design of Offshore Units [77]

A.6 Safety Management

RenewableUK Wave & Tidal Health & Safety Guide [78]

RenewableUK Offshore Wind and Marine Energy Health and Safety Guidelines [79]

ISO 12100 Safety of Machinery [80]

DNV-ST-N001 Marine operations standard (replaced DNV-OS-H101) [81]

A.7 TRL and TPL Definitions

DOE Technology Readiness Assessment Guide, see Table 1 [8]

NASA TRL definitions [82]

Appendix 2 Technology Readiness Levels for Supply Chain Study for WestWave – provides TRL functional definitions for wave power devices and a verification checklist [37]

OES IA Guidelines for the Development & Testing of Wave Energy Systems (2010) has a TRL table on page 82 [28]

J. Weber, "WEC Technology Readiness and Performance Matrix – Finding the Best Research Technology Development Trajectory," from International Conference on Ocean Energy and European Wave and Tidal Energy Conference [12]

J. Weber et al. “WEC Technology Performance Levels (TPLs) – Metric for Successful Development of Economic WEC Technology,” from European Wave and Tidal Energy Conference [10]

NREL: Technology Performance Level Assessment: Wave Energy Converters [11]

A.8 Miscellaneous

DNV-0S-D201 Electrical Installations, DNV, October 2013 [83]

Review of the Risk Assessment of Buoyancy Loss (RABL) Project, 2003; this document exemplifies the importance of risk management [84]

Tidal Turbines That Survive?, presentation from University of Southampton [85]

Reliability-Based Fatigue Design of Marine Current Turbine Rotor Blades, master’s thesis by Shaun Hurley [86]

Tidal Current Turbine Fatigue Loading Sensitivity to Waves and Turbulence – a Parametric Study, by Graeme Mccann, legacy DNV GL [87]

Evaluation of the Durability of Composite Tidal Turbine Blades, by Peter Davies, et al., provides framework for rotor blade qualification [88]

DNV-RP-C205, Environmental Conditions and Environmental Loads, DNV, September 2021 [89]

Appendix B. MEC Lessons Learned (Publicly Available Information)

The following contains publicly available articles or reports on MEC lessons learned, collected for the express purpose of managing negative risk in future projects. All articles were drawn from websites accessible in January 2024 and, as such, only include information in the public domain. No endorsement or repudiation of the designs or companies mentioned in the articles is implied by their inclusion in this list; moreover, this report does not make any claims regarding the veracity of the information present in the linked articles.

The following are some common themes from this information:

- Inadequate regulatory planning results in delays and costs
- Rotor blade failures
- Operational loads and tidal/wave resources have not always been well understood
- Transporting/installing the system may have unanticipated loads/complexities
- Buoyant components have sinking risk
- Small failures may cascade to system failures.

B.1 Failure During Installation due to Inadequate Tank Testing:

- http://www.publications.parliament.uk/pa/cm200001/cmselect/cmsctech/291/1031409.htm

B.2 Manufacturing Faults and Structural Failures:

- http://www.oceanrenewable.com/2011/09/12/atlantis-resources-corporation-connects-1mw-tidal-turbine-to-the-national-grid/
- http://www.bbc.co.uk/news/uk-scotland-highlands-islands-11492829

B.3 Breach of Water Integrity of Compartments or Equipment:

- https://www.renewableenergyworld.com/baseload/hydropower/while-finaveras-buoy-sinks-hopes-of-harnessing-ocean-energy-survive-50510/#gref

B.4 Mooring Failure/Breach of Water Integrity of Compartments or Equipment/Bankruptcy:

- http://cleantechnica.com/2010/05/22/massive-offshore-waves-sink-australias-oceanlinx-wavepower-pilot/
- https://www.heraldsun.com.au/news/national/oceanlinx-forced-to-tow-wave-energy-converter-out-of-troubled-waters-off-the-fleurieu-peninsula/news story/169c6a151ffe939c2c4f03a189de2274
- http://www.abc.net.au/news/2014-04-01/oceanlinx-wave-energy-generatorjpg/5359456
- http://www.abc.net.au/news/2014-04-02/support-aired-for-oceanlinx-project-as-creditors/5361898
- http://www.businessspectator.com.au/news/2014/4/2/renewable-energy/oceanlinx-goes-bankrupt-owing-10m
- http://www.offshorewind.biz/2014/04/15/video-oceanlinx-wave-energy-generator-stuck-off-carrickalinga/

B.5 Bankruptcy:

- https://www.theengineer.co.uk/content/news-analysis/wave-goodbye-aquamarine-power-folds-due-to-lack-of-private-sector-support/

B.6 Structural Failure:

- http://www.greentechmedia.com/articles/read/a-big-setback-for-tidal-power
- http://www.cbc.ca/news/canada/nova-scotia/failed-tidal-turbine-explained-at-symposium-1.1075510
- https://www.cbc.ca/news/canada/nova-scotia/turbine-damage-stalls-fundy-tidal-power-test-1.926011

B.7 Lost Anchors/Regulatory:

- http://www.oregonlive.com/environment/index.ssf/2013/08/oregon_wave_energy_stalls_off.html

B.8 Electrical Failures and Shore Connector Failures:

- https://bangordailynews.com/2013/04/10/news/down-east/year-one-of-eastport-tidal-turbine-research-presents-challenges/

B.9 Technical Problems with Hydraulics/Bankruptcy:

- https://phys.org/news/2009-03-portuguese-wave-power-snake-dead.html
- https://www.imeche.org/news/news-article/wave-energy-pioneer-pelamis-calls-in-administrators#:~:text=Wave%20energy%20specialist%20Pelamis%20Wave,advanced%20wave%20energy%20technology%20companies.

B.10 Intermittent Fault/Mechanical Defect/Bankruptcy:

- https://www.bbc.com/news/uk-wales-politics-38236014

B.11 Stakeholder Engagement:

- https://www.bbc.com/news/uk-england-hampshire-36171792

B.12 Breach of Water Integrity of Compartments or Equipment:

- https://theorkneynews.scot/2019/03/26/problems-for-wellos-penguin-wave-energy-device/

B.13 Regulatory:

- https://www.nytimes.com/2023/04/29/world/canada/sustainable-marine-tidal-energy-suspended.html

B.14 Lessons Learned:

- https://webassets.bv.com/2020-06/MeyGen%20Lessons%20Learnt%20Full%20Report_0.pdf

Appendix C. Example Risk Registers and FMEAs

The title page from this report contains recommended templates for a risk register [30] and FMECA [32].

Additionally, the following are links to publicly available risk registers and FMEAs (or FMECAs). These links are provided for consideration and learning by the reader and are not recommendations or endorsements by the authors of this MEC risk framework:

C.1 Risk Register Methods, Templates, and Examples

- https://mhkdr.openei.org/search?q=risk
- https://www.dot.state.mn.us/pm/risk.html
- https://www.osti.gov/biblio/1557617
- http://www.diva-portal.org/smash/get/diva2:907006/FULLTEXT01.pdf
- https://www.energy.gov/management/articles/microsoft-word-centralized-riskregister-user-guide-1-31-10doc
- https://globalclimateactionpartnership.org/app/uploads/2015/07/Risk-Quantification-and-Risk-Management-in-Renewable-Energy-Projects.pdf
- https://tethys.pnnl.gov/sites/default/files/publications/Gatzert-2014.pdf

C.2 Example FMEAs and FMECAs

- "Failure Mode Effects Analysis (FMEA) Template (XLS)" downloadable from https://asq.org/quality-resources/quality-tools
- "FMEA-template.xls" downloadable from https://www.lehigh.edu/~intribos/Resources/
- https://www.sciencedirect.com/science/article/pii/S0142061510000281
- https://www.researchgate.net/publication/338828600_Risk_Analysis_of_Wave_Energy_Converter_System_Using_Failure_Mode_and_Effect_Analysis
- https://www.researchgate.net/publication/285782218_Design_Development_and_Experimentation_of_Deep_Ocean_Wave_Energy_Converter_System
- https://www.ijser.in/archives/v3i9/IJSER15469.pdf