Technology Collaboration Programme
by IEA

2023

AN INTERNATIONAL EVALUATION AND GUIDANCE

FRAMEWORK FOR OCEAN ENERGY TECHNOLOGY

OES OCEAN ENERGY SYSTEMS

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Photo on cover page:
CorPower C4 device in northern Portugal (Courtesy: CorPower Ocean)

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CONTRIBUTORS

The primary contributors to this document are as follows:

The IEA-OES community

- The IEA-OES ran a workshop on measurement of success in ocean energy (including the approach to Task 12) at its Executive Committee Meeting, alongside the International Conference on Ocean Energy (ICOE) 2018. This provided valuable insight into the application of evaluation techniques in the global renewable energy sector. Valuable input from other IEA-OES partners (1) and their selected technical representatives has been gathered through the process of reviewing and iterating Task 12 deliverables, including a further review workshop at the Executive Committee meeting alongside the Ocean Energy Europe in 2019.

The European Commission

Matthijs Soede

- The European Commission funds ocean energy technology research, development and demonstration through a range of Research and Innovation programmes such as Horizon 2020, FP-7 and Interreg Europe.
- The Commision has funded a series of research and innovation activities which have contributed to the development of evaluation techniques for ocean energy. In particular, through the European Energy Research Alliance (EERA) Ocean Energy Joint Programme (2) and the Ocean ERA-NET (3) funding schemes, Wave Energy Scotland, the US Department of Energy and the Sustainable Energy Authority of Ireland (SEAI) ran a series of workshops aiming to develop consensus on metrics (Evaluation Criteria) for the ocean energy sectors. The Energy Technology and Innovation Platform for Ocean Energy, ETIP Ocean (4), has run a series of webinars and workshops, some of which focussed on metrics (Evaluation Criteria).

US Department of Energy (US DOE) Water Power Technologies Office

Lauren Ruedy, Tim Ramsey, Elaine Buck, Jochem Weber (NREL) and David Hume

- The US DOE funds technology research, development and demonstration through specifically targeted calls and has gathered valuable experience of evaluation and selection processes for ocean energy. The DOE also ran the flagship Wave Energy Prize (5), a competition managed through application of criteria such as the ACE metric (Average Climate Capture Width per Characteristic Capital Expenditure).

- The DOE funds Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) along with partners to complete the Wave-SPARC (6) programme . This programme has developed Structured Innovation processes, focusing on methods for holistic evaluation of technologies, from low TRL to high TRL, through the Technology Performance Level assessment system. The DOE also funds the Pacific Northwest National Laboratory (PNNL) to deliver many ocean energy activities, including implementation of the OES-Environmental task examining environmental effects of marine renewable energy development.

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- The University's Institute for Energy Systems is specialist in ocean energy roadmaps, action plans and strategies. It plays a leading role in international collaboration activities, chairing the European Energy Research Alliance (EERA) Ocean Energy Joint Programme (JP) and collaborating on numerous European ocean energy projects.
- Until January 2021, Edinburgh held the position as the Chairperson of the International Energy Agency's (IEA) Ocean Energy Systems (OES) programme.

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- Tecnalia has extensive experience of ocean energy technology development including structured approaches to innovation, evaluation and decision making.
- Tecnalia coordinated the DTOceanPlus (7) project, funded by the European Commission's Horizon 2020 programme under grant agreement number 785921. The project has developed advanced design and evaluation tools for ocean energy technologies. Free download from https://gitlab.com/dtoceanplus
- Tecnalia participates in several technical groups within the International Electrotechnical Committee (IEC) TC114 and chairs the corresponding Spanish Technical Committee.
- Tecnalia is a board member of Ocean Energy Europe, which identifies a stage gate approach as a key initiative to guide Ocean Energy development, and co-chairs the EERA Joint Programme on Ocean Energy.
- Tecnalia participates in ETIPOcean (European Technology and Innovation Platform on Ocean Energy) and has led the development of a Strategic Research and Innovation Agenda.

Wave Energy Scotland (WES)

Jonathan Hodges, Jillian Henderson, Elva Bannon, Matthew Holland and Ruairi Maciver

- WES, established by the Scottish Government, is running a research, development and innovation programme (8) based on a competitive stage gate process. WES has significant experience of technology evaluation and decision-making processes.
- WES is a partner in the DTOceanPlus (7) project, leading development of a Stage Gate tool for guidance and evaluation of ocean energy technologies.
- WES is a partner on OceanSET, supporting the implementation plan of the European Strategic Energy Technology Plan (SET Plan). This project received funding from the European Union's Horizon 2020 programme under grant agreement number 840651. WES is contributing experience on technology development and evaluation, assessing financial support requirements and developing sector monitoring processes.
- WES is a committee member for input to the IEC 62600 series of Technical Specifications.

OES Environmental and Pacific Northwest National Laboratory

Andrea Copping and Lysel Garavelli

- OES-Environmental (formerly known as Annex IV) was established by the International Energy Agency (IEA) Ocean Energy Systems (OES) in January 2010 to examine environmental effects of marine energy development. The U.S. Department of Energy (DOE) leads the tasks for the United States, partnered with the U.S. Bureau of Ocean Energy Management (BOEM) and the U.S. National Oceanic and Atmospheric Administration (NOAA). OES-Environmental is implemented by Pacific Northwest National Laboratory (PNNL), who acts as the Operating Agent. Tethys acts as the platform on which OES-Environmental activities are coordinated and recorded. (https://tethys.pnnl.gov)
- Marine energy is an emerging industry that faces regulatory challenges associated with potential environmental impacts, around which there is a high degree of uncertainty. OES-Environmental mobilizes information and practitioners from OES nations to coordinate research that can progress the industry in an environmentally responsible manner. A key component of this effort involves making existing information available and accessible.

International
Electrotechnical
Commission

International Electrotechnical Commission – Technical Committee 114 (IEC TC 114)

Jonathan Colby

- The IEC is a global, not-for-profit membership organization, whose work underpins quality infrastructure and international trade in electrical and electronic goods. The IEC publishes around 10 000 IEC International Standards which together with conformity assessment provide the technical framework that allows governments to build national quality infrastructure and companies of all sizes to buy and sell consistently safe and reliable products in most countries of the world. IEC International Standards serve as the basis for risk and quality management and are used in testing and certification to verify that manufacturer promises are kept. The standards produced by TC 114 (Marine energy Wave, tidal and other water current converters) will address:
  - terminology;
  - management plans for technology and project development;
  - performance measurements of marine energy converters;
  - resource assessments;
  - design and safety including reliability and survivability;
  - deployment, commissioning, operation, maintenance, retrieval and decommissioning;
  - electrical interface, including array integration and / or grid integration;
  - testing laboratory, manufacturing and factory acceptance;
  - additional measurement methodologies and processes.

Mocean BlueX device operating at EMEC, Scotland
Courtesy: Mocean Energy © Colin Keldie

EXECUTIVE SUMMARY

Nations across the world recognise the potential benefits of ocean renewable energy, pursuing the development of new technologies and projects to take advantage of their natural resources. Wave and tidal stream projects, and the associated technology, have generated interest from governments, investors and developers, all keen to help build the sector. The successful transition from nascent technology to commercial proposition relies on the most efficient use of available resources, and world class R&D.

This document is an output of IEA-OES Task 12, an activity funded by the members of the International Energy Agency (IEA) Ocean Energy Systems (OES) Technology Collaboration Programme (TCP). The scope of this document includes technology associated with utility-scale electricity generation from ocean waves and tidal streams. Future Task 12 activity will expand to incorporate other forms of ocean energy.

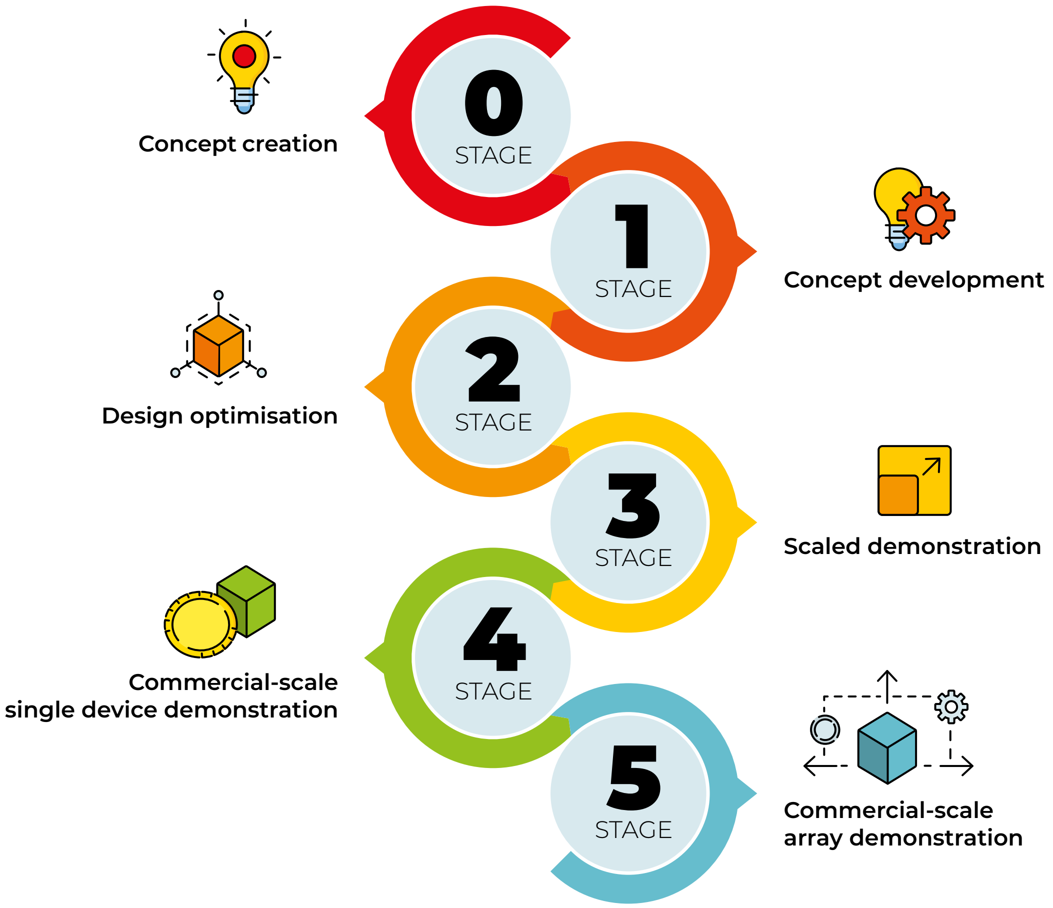
Electricity is likely to be the main output ocean energy technologies; however, it is recognised that alternative markets are emerging where other functionality may be desirable. Most of the guidance presented in this report are still valid for such alternative applications, but may require case by case adaption, e.g. for situations where electricity is not the primary output.

The objectives of Task 12 are:

- Build international consensus on ocean energy technology evaluation
- Guide appropriate and robust activities throughout the technology development process
- Share knowledge and promote collaboration
- Support decision making associated with technology evaluation and funding allocation

This document intends to support international efforts by presenting a framework for technology evaluation and guidance of engineering activity, ensuring that decision-makers have consistent information available to them.

The framework breaks the development process into six stages, from concept creation to commercialisation:



The activities and evaluations presented in the stages reflect the increasing knowledge, confidence and funding required as a technology matures. The framework builds the foundations of a clear, unambiguous evaluation methodology. It is noted that the path of a technology through the stages may not be linear, with iterations and resulting stage repeats often being necessary to deliver cost-efficiency and technical success.

International acceptance of a common approach to technology development and evaluation brings the following benefits:

- Clarity in the expectations from different stakeholders during each stage of development, bringing clearer communication
- Consistency in the use of terminology, and the process to evaluate technology, ensuring a level playing field
- Stakeholders working together to build confidence and transparency in the sector
- Efficient decision-making processes promoting direction of funding to the technologies with highest chances of commercial success
- Technology development processes consistent across the world, leading to more international collaboration more globally transferrable technology

Task 12 has taken an iterative approach, engaging numerous stakeholders from across the ocean energy sector and building upon previous work. Beyond the release of this document, Task 12 will continue engagement and collaboration with standards institutions, progressing towards a complete and internationally agreed process for maturation and evaluation of ocean energy technology.

This 2nd Edition of the document represents an update in response to feedback from international adoption of the framework. Additions include and expansion to consider sustainability and elaboration of the close relationship between this framework and the guidance provided by other organisations, such as standards institutions.

LIST OF ABBREVIATIONS

CAPEX	Capital Expenditure
DLC	Design Load Case
DEG	Dielectric Elastomeric Generator
ETIP Ocean	Energy Technology and Innovation Platform for Ocean Energy
EERA	Ocean Energy Joint Programme, European Energy Research Alliance
FEED	Front End Engineering Design
FMEA	Failure Modes and Effects Analysis
FOA	Funding Opportunity Announcements (United States DOE)
GW	Gigawatt
HSE	Health, Safety and Environment
H_{m0}	Significant wave height
H_{max}	Maximum wave height
ICOE	International Conference on Ocean Energy
IEA-OES	International Energy Agency, Ocean Energy Systems
IEC	International Electrotechnical Commission
KPI	Key Performance Indicator
LCOE	Levelised Cost of Energy
NREL	National Renewable Energy Laboratory
MRL	Manufacturing Readiness Level
MTTF	Mean Time to Failure
MW	Megawatt
O&M	Operations and Maintenance
OES	Ocean Energy Systems (IEA), Technology Collaboration Programme
Ocean ERA-NET	Network of 15 national and regional funders across Europe
OPEX	Operational Expenditure
PTO	Power Take-Off
ROV	Remotely Operated Vehicle
R&D	Research and Development
RD&D	Research, Development and Demonstration
SNL	Sandia National Laboratories
SEAI	Sustainable Energy Authority of Ireland
TEC	Tidal Energy Converter
TPL	Technology Performance Level
TRL	Technology Readiness Level
U_{10}	Mean wind speed at 10 m above mean sea level
ULS	Ultimate Limit State
UN	United Nations
DOE	United States Department of Energy
T_e	Energy Period
WEC	Wave Energy Converter
WES	Wave Energy Scotland

Verdant Power assembling their Kinetic Hydropower System tidal power turbines
Courtesy: Verdant Power

1 INTRODUCTION

1.1

IEA-OES TASK 12 SCOPE AND FUTURE ACTIVITY

This document is an output of IEA-OES Task 12, an activity of the International Energy Agency (IEA) Ocean Energy Systems (OES) Technology Collaboration Programme (TCP).

The task is led by the European Commission and delivered by Wave Energy Scotland (WES), the United States Department of Energy (DOE), Tecnalia (Spain) and other representatives of the IEA-OES Executive Committee.

The **objectives of Task 12** are:

- Build international consensus on ocean energy technology evaluation
- Guide appropriate and robust activities throughout the technology development process
- Share knowledge and promote collaboration
- Support decision making associated with technology evaluation and funding allocation

Consensus on technology evaluation and technology development activities will bring significant **benefits** for various stakeholders in the ocean energy sectors:

- Clarity in the expectations from different stakeholders during each stage of development, bringing clearer communication
- Consistency in the use of terminology, and the process to evaluate technology, ensuring a level playing field
- Stakeholders working together to build confidence and transparency in the sector
- Efficient decision-making processes promoting direction of funding to the technologies with highest chances of commercial success
- Technology development process consistent across the world, leading to more international collaboration more globally transferrable technology

The goal of the wider activity is to create a complete and unambiguous process for the development and evaluation of ocean energy technologies throughout all stages of development.

This requires clear **definition** of:

- Stage Activities – the engineering activities carried out by developers,
- Evaluation Criteria – the parameters used to evaluate achievement
- Evaluation Method – the process used to calculate Criteria

The immediate goal of this document is to form a solid foundation for the unambiguous development and evaluation process, accommodating formal standards and guidelines, where they already exist, and providing cues for the future production of other supporting standards and guidelines where required. The goal is not to replace existing technical specifications, standards and guidance, but to unite them with a common purpose. Beyond delivery of this document, Task 12 will continue engagement and collaboration with standards institutions, progressing towards internationally agreed process for maturation and evaluation of ocean energy technology.

The scope of this document includes technology associated with electricity generation from ocean waves and tidal streams and covers the full technology development from concept creation to commercial readiness. Future Task 12 activity will expand to incorporate other forms of ocean energy. Electricity is likely to be the main output for ocean energy technologies however it is recognised that alternative markets are emerging where other functionality may be desirable. Most of the guidance presented in this report is still valid for such alternative applications, but may require case by case adaption, e.g. for situations where electricity is not the primary output.

The document is intended to be widely applicable to subsystems (e.g. power take-off, mooring and connection systems), devices (wave energy converters and tidal stream energy converters) and arrays of devices.

Task 12 has followed an iterative approach, with each iteration adding more detail to the framework for technology evaluation and guidance of engineering activity, taking input from IEA-OES member countries and their representatives. This work builds upon a series of workshops and collaboration activities, listed in Annex A – Preceding Activity.

1.2 DOCUMENT STRUCTURE

This document is structured as follows:

Section 1 • Introduction, terminology and background
A high-level discussion of the importance of technology evaluation and guidance in the ocean energy sector. This section introduces the concept and content of the Evaluation and Guidance Framework.
Target Audience: policy makers, public and private investors, technology developers and standards institutions

Section 2 • Evaluation and Guidance Framework
Detail of the stages and topics included in the Framework and discussion of the integration of topics into a holistic evaluation process.
Target Audience: public and private investors, technology developers and standards institutions

Section 3 • Evaluation Criteria & Stage Activities
Detail of the criteria used to evaluate technologies and the recommended engineering activities to be carried out at each stage of the technology development process.
Target Audience: public and private investors, technology developers and standards institutions

1.3 TERMINOLOGY

The contents of the Framework for technology evaluation and guidance of engineering activity are as follows:

Stages

Defined periods of the development process, aligned with phases of funding and decision points. *Alternative terminology: Phases.*

Evaluation Areas

The key areas in which to measure the success of technology, in order to demonstrate progress and achieved performance.

Evaluation Criteria

The specific parameter(s) used to evaluate how well a technology satisfies the Evaluation Area. *Alternative terminology: Metrics, key performance indicators (KPIs).*

Evaluation Method

The calculation method and data sources required to quantify the Evaluation Criteria – *detailed evaluation methods will be presented in the growing body of Technical Specifications, standards and protocols being developed by institutions, such as the International Electrotechnical Commission (IEC), and are not in scope of this document.*

Thresholds

The minimum or maximum value or score which must be achieved in each Evaluation Criteria to meet requirements. *Thresholds are specific to technologies, projects, markets and investors; therefore, a standard value cannot be defined. Thresholds are not in scope of this document.*

Stage Activities

The engineering activities that occur during a technology development Stage. Clearly defined activities provide consistency in expectation between developers and investors, ensuring projects deliver the appropriate data to support the Evaluation Method and resulting Evaluation Criteria.

Stage Entry Requirements

The activities which must be successfully completed for a technology to be eligible for a stage of development (*nominally these represent adequate completion of the Stage Activities from previous stages* and are not presented separately in this document*).

***A note on Technology Readiness Levels (TRL):**

TRLs were originally devised by NASA as a high-level method to determine how advanced or 'ready' a technology was for use in an application. It gives a list of activities or milestones which need to be met to achieve a particular level. A similar approach has been adopted by other organisations and sectors to give a basic means of assessing a technology.

The definitions of each level do not indicate how well any of these milestones should have been met, nor evaluate how well the technology performs against its requirements.

This Document outlines the evaluation of performance against specified Evaluation Criteria and the standard to which the Stage Activities have been completed, complementing rather than replacing the TRL scale. TRL definitions for the Ocean Energy sector have been developed in (25).

AWS Waveswing during deployment at EMEC, Scotland
Courtesy: AWS Ocean Energy

1.4 THE LANDSCAPE OF EVALUATION CRITERIA

Evaluation and decision making occur at all levels in all industries, from technology developers selecting components to national governments planning long-term strategic investments. The Evaluation Criteria, and information which supports evaluation of performance against each, vary widely depending on the decision to be made and the implication of that decision.

At the highest level of decision making in the energy sector, a set of Evaluation Criteria may be specific to electricity generation, but generic to the types of generation technology in the sector (nuclear, gas, renewables).

As the evaluation moves to lower levels within the energy sector, the Evaluation Criteria may become specific to the generation type (e.g. renewables) but generic across sub-divisions of that type (e.g. ocean energy technology).

At the next level down, the Evaluation Criteria may become more specific again (e.g. wave energy technology) and even specific to a type of wave energy device or a market (e.g. grid-scale utility electricity generation or remote communities).

Figure 1 illustrates various levels of focus of decision making, from strategy development down to R&D direction, alongside the types of Evaluation Criteria which might be used. These are colour-coded to identify how generic or specific they are. This document is focused on the types of evaluation criteria that are generic to ocean energy technologies, while maintaining awareness of those which become specific to markets, resources or technology types.

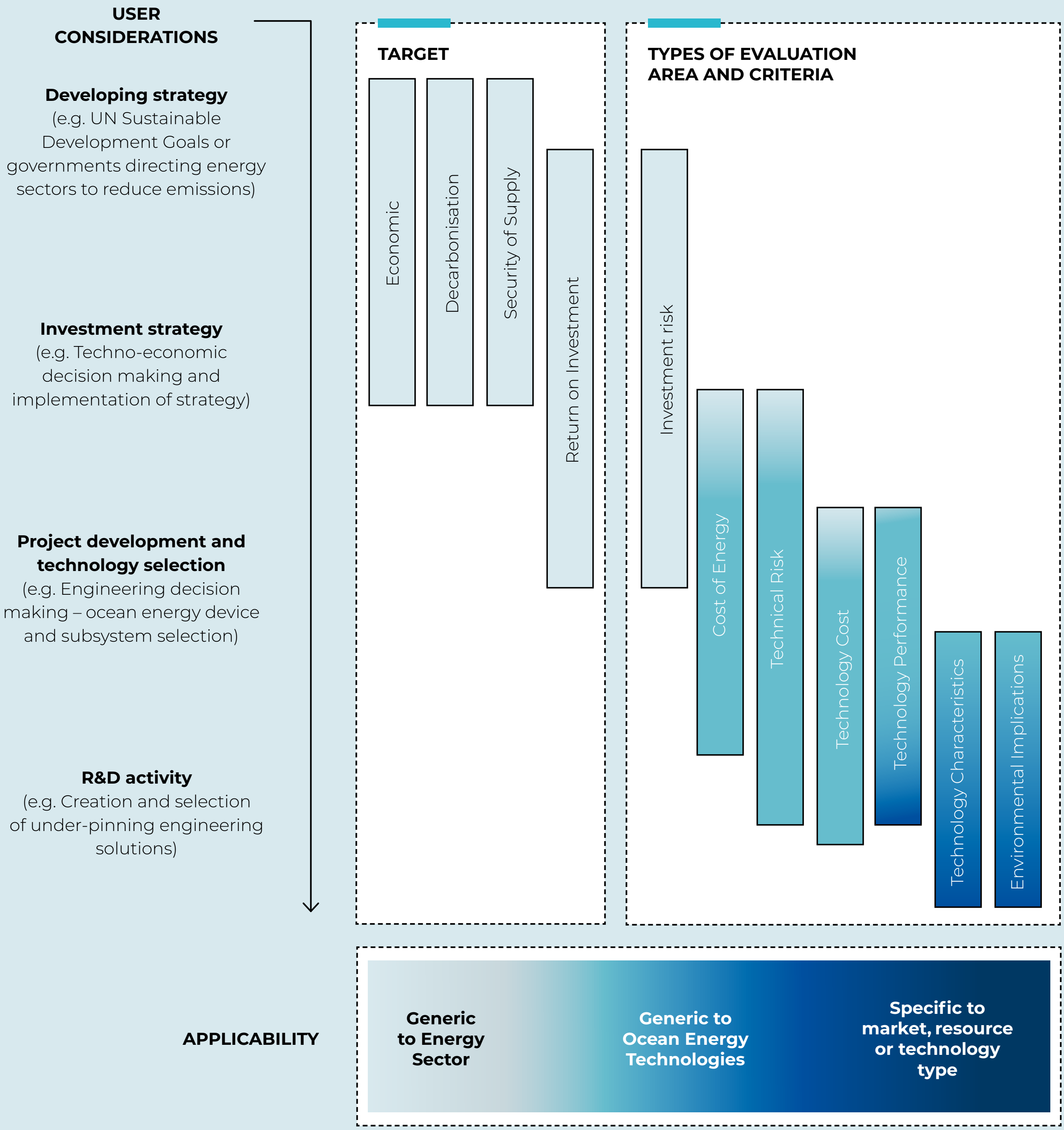


Figure 1 Hierarchy of Evaluation Areas and Criteria types

1.5 TYPES OF EVALUATION IN OCEAN ENERGY

The end goal of the evaluation process is to have a completely objective evaluation of how a technology performs against the criteria. The information required to carry out a fully objective, quantitative evaluation is not always available, especially at the early stages (low detail) of the development process. This means that the evaluation approach must evolve, taking in to account the development stage, activities completed and the available information. Evaluation approaches can be qualitative and/or quantitative as appropriate, with both being employed in the ocean energy sector, generally progressing from qualitative to quantitative as technology matures. There is a link between the qualitative or quantitative nature of an evaluation and the level of objectivity it achieves. In general, qualitative evaluations are naturally subjective, being based in part on the opinion of the person evaluating it (the assessor). As information becomes more quantitative, the evaluation can become more objective. These types of evaluation are characterised in Figure 2.

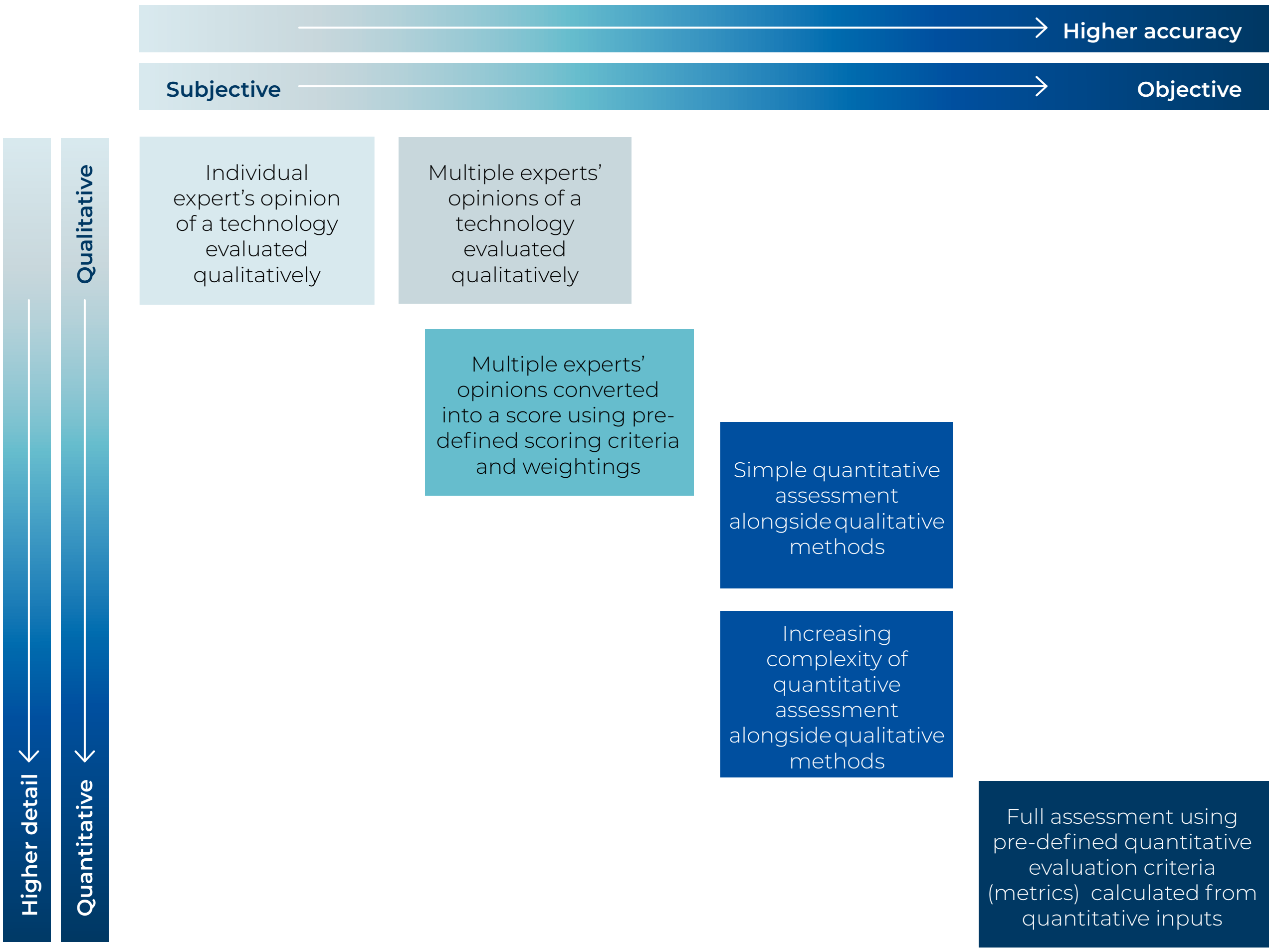


Figure 2 Examples of evaluation which are qualitative/ quantitative and subjective/ objective

The subjectivity of qualitative methods (i.e. an expert assessor evaluating a qualitative description of a technology and assigning a numerical score) can be managed by using clear, specific scoring criteria. These scoring criteria bring improvement when devised using industry best practice and a clear understanding of fundamental technology requirements. Despite such management, subjectivity will always remain and be affected by the technology developers' ability to describe their technology or explain their achievements. Subjectivity can also be reduced by having a panel of experts involved in a review. Examples of this type of managed scoring can be found in the European Commission's Horizon 2020 evaluation process, Wave Energy Scotland stage gate programme (8) and the Technology Performance Level (TPL) evaluation process developed by NREL and Sandia under the Wave-SPARC programme (6) in the USA.

Where quantitative approaches are used, the complexity of the method applied to calculate the Evaluation Criteria must align with the complexity of the input data available. The complexity of these input data arises from the Stage Activities producing them, with these evolving as the technology matures. At early stages of development, the quantitative data can be sparse or resulting from simple, high-level analysis. In these cases, the quantitative input data can be fulfilled by using the best available information, for example typical benchmarks for across the sector. This stage-by-stage improvement in the complexity (and hence the accuracy and fidelity) of quantitative input data is built into the progression of Stage Activities recommended in section 3.

It is important to note that a combination of qualitative and quantitative evaluations is often valuable; qualitative information (e.g. a description of the characteristics of a technology) often adds to the assessors' (potentially investors') understanding of a technology's development route, improving the confidence they derive from the detailed quantitative evaluation results.

Minesto' tidal kite to be deployed at Faroe Islands
Courtesy: Minesto

1.6
SYSTEM BOUNDARIES

The ocean energy sector requires evaluation criteria which can be applied to technology from different levels of aggregation, i.e. subsystems, individual wave or tidal stream devices, and arrays of devices. However, some Evaluation Criteria can only be fully assessed at array-level (numerous devices deployed together with the necessary balance of plant). Therefore, a subsystem must be placed in context of a device and that in turn placed in the context of an array, to be able to evaluate the impact of that subsystem on array level performance. Figure 3 illustrates the levels of aggregation of technologies, continuing beyond array level to consider the installation of that array in a specific geographical site (environment) and the commercial aspects of an ocean energy project.

An example of the need to place an evaluation into context is the assessment of cost for a PTO. The PTO is an integral component of a wave or tidal stream device, with its design requirements and performance being determined by the device, control system, the loads experienced by the components. The cost of the PTO, and the amount of electricity generated, is not purely based on that subsystem so it is not easy or appropriate to calculate the LCOE for a PTO alone; it must be taken in the context of an entire project. Typical values from wider sector experience can be used here and the development of standard operating conditions (wave and tidal current environments) to facilitate direct comparison of technologies is valuable.

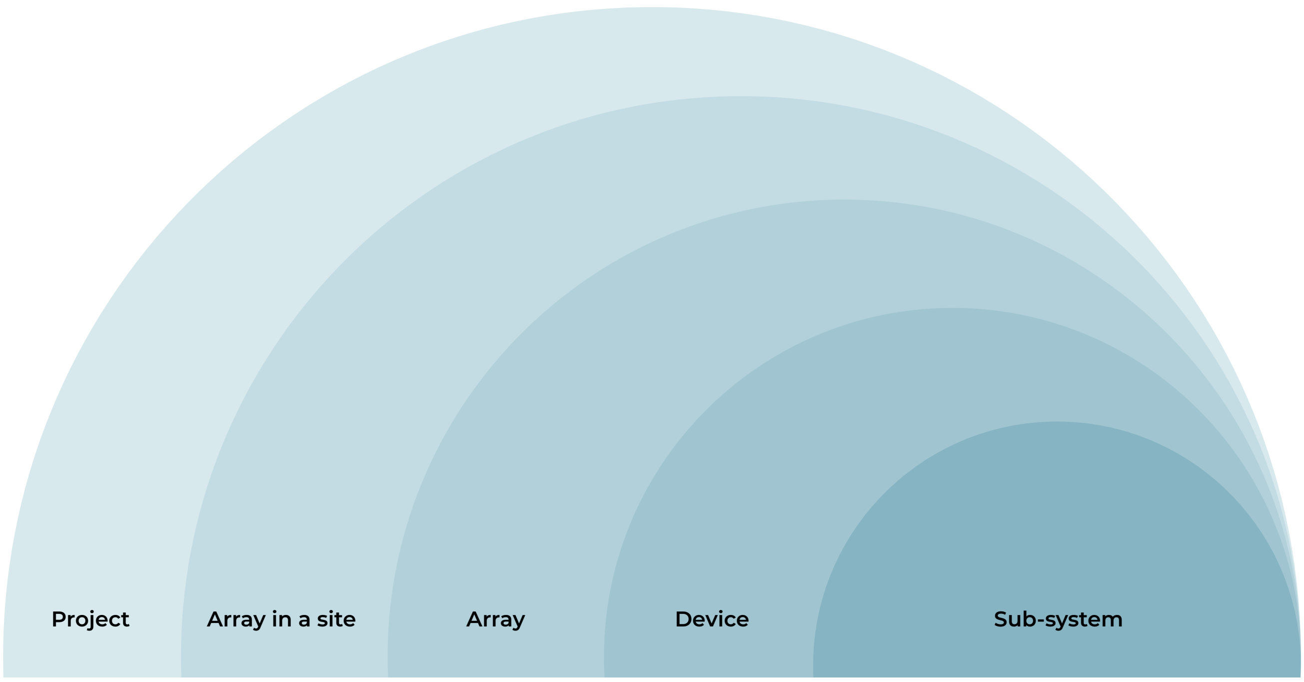


Figure 3 Illustration of various system boundaries for evaluation

1.7 COHERENT APPLICATION OF GUIDANCE, STANDARDS AND CERTIFICATION

The pathway from early-stage technology to commercial exploitation requires a varying mix of support and guidance, from public sector funding through various types of private investment. The goals of these supporters are wide ranging, from socio-economic growth and domestic infrastructure requirements, through to pure financial gain. Despite the differing objectives of these parties, consensus among them on the development path and the fundamental characteristics of an attractive technology enables the support provision to operate more efficiently and with a higher likelihood of success.

Like more mature sectors, the ocean energy sector has a growing body of a guidance and support provision, designed to promote and accelerate commercial exploitation of prospective technologies. As the interests and objectives of stakeholders evolve along the development pathway, so does the guidance required to support the sector's passage – from early-stage conceptualisation to commercial readiness.

This document is written to provide recommendations that are complimentary and coherent with other sources of guidance from the International Electrotechnical Commission (IEC) Technical Committee 114 (IEC TC 114[1])and the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy (IECRE[2]). Ongoing collaboration between these organisations intends to promote the value of each source of guidance and to illustrate how they complement each another. Further guidance is also provided by the Technical Committees of the International Towing Tank Conference (ITTC[3]) with a liaison in place between IEC TC 114 and the ITTC.

At the highest-level[4], the function of the sources of guidance are:

1. IEA-OES Evaluation and Guidance Framework
Helping funders select the most promising technologies by agreeing *what development activities and key evaluation parameters they should expect from developers*

2. IEC Technical Specifications
Helping developers advance their technologies correctly by detailing *how activities and evaluations are carried out*

3. ISO/IEC Certification Bodies and Test Laboratories
Helping developers test and verify their achievements by *adhering to standards and confirming results*

4. IECRE System
Underpinning technical quality by *assessing conformity against standards*

Figure 4 adds detail to the focus and role of each source of guidance.

1 https://iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1316,25
2 https://www.iecre.org/home
3 https://ittc.info/about-ittc/
4 More detail on the roles and objectives of these sources of guidance is available in an associated document co-authored by OES, IEC and IECRE https://www.ocean-energy-systems.org/publications/oes-documents/guidelines/document/supporting-ocean-energy-technology-development-and-commercialisation/

IEA-OES Framework
- Innovation
- Selection
- Prioritisation
- Managing risk

IEC Standards
- Development
- Design
- Operation
- Assessment
- Quantifying risk

Certification Bodies and Test Laboratories
- Third-party verification
- Adherence to standards
- De-risking
- Ensuring credibility

IECRE System
- Conformity assessment
- International recognition
- Investment readiness
- Commercial suitability
- Insurability

Figure 4 Focus of key sources of guidance and support in the ocean energy sector

The guidance and support mechanisms have different, but complimentary, benefits and overlapping primary target audiences:

- **IEA-OES Framework for Ocean Energy Technology – used primarily by public funders and technology developers.**
  The OES Framework helps funders to select a cohort of more promising early-stage technologies and supports their further development by enabling public funders to recognise their attractive characteristics. Development in accordance with this Framework helps build evidence of a technology's pedigree and readiness for the next stage of funding and technical progress.
- **IEC Technical Specifications and Standards – used primarily by technology developers, R&D providers, manufacturers, test sites and third parties.**
  International, consensus-based, standards ensure that technologies are developed, tested, and evaluated using a common set of appropriate best practice methodologies. Technical input is provided in Working Groups by subject matter experts organized within National Committees.
- **Certification Bodies and Test Laboratories – used primarily by technology developers and manufacturers.**
  Third parties provide independent evaluation of compliance with technical standards to create confidence among regulators, investors, customers, and insurance providers, among others. Third party competence and quality are confirmed with Peer Assessment in the IECRE System, based on compliance with relevant quality standards.
- **IECRE Conformity Assessment – used primarily by technology developers, manufacturers, test sites and third parties.**
  The IECRE System enables independent conformity assessment of a technology to confirm that it has been designed, manufactured, and tested according to international, consensus-based standards. Mutual recognition of IECRE Statements, Test Reports and Certificates reduces barriers to market entry globally and increases confidence in the product.

THE VALUE OF COHERENT APPLICATION OF GUIDANCE, STANDARDS, AND CERTIFICATION

The growing ocean energy sector needs confidence in the technology upon which it is based. Knowledge that the technology developers are using the available guidance helps to build that confidence for all stakeholders at all stages of the process.

Table 1 describes the value of each type of guidance at the early, mid and late-stages of development, in terms of the *impact* it has on stakeholder confidence. This detail further illustrates how the sources of guidance support, or utilise, each other's recommendations to form a continuous flow of technology guidance.

Stage of development	IEA-OES Framework	IEC Standards and Guidelines	Certification Bodies, Test Laboratories and the IECRE System
Early	Guidance of development and evaluation approaches for public funders. *Gives public funders confidence that developers are targeting key characteristics and appropriately demonstrating performance through rigorous engineering.* *Public funders gain confidence that incoming technologies have appropriate development pedigree, targets and experience.*	Technology Qualification and guidance for small scale-model testing; Initial resource assessment and site characterization. *Early-stage investors build confidence in rigour of concept development process.*	Third party review of early-stage development via Technology Qualification and validation of scale-model testing results. *Creates confidence that performance presented is credible for further development.*
Mid		Design standards for technology developers; Guidance for medium to large-scale model testing; Enhanced resource assessment and site characterization; Full-scale performance assessment. *Investors build confidence that design processes will yield a reliable, survivable technology.*	Third-party evaluation and conformity assessment. *Creates confidence that performance presented is credible for further development and commercialization.*
Late		Design standards for technology developers; Detailed resource assessment and site characterization; Full-scale performance assessment; Site-specific system performance. *Investors and customers build confidence in the suitability of the technology for safe and reliable commercial exploitation.*	Certification of technologies against prescribed processes. *Supports regulatory agencies and insurers and delivers investor confidence while reducing barriers to market entry, expediting commercial deployments globally.*

Table 1 Demonstrating the value and relevance of guidance through the technology development process

Wave Swell Energy prototype, King Island, Tasmania Courtesy: Wave Swell Energy

2

EVALUATION AND GUIDANCE FRAMEWORK

2.1 TECHNOLOGY DEVELOPMENT STAGES

Division of the technology development process into Stages provides clarity on expectations for all stakeholders. Public and private investors and technology developers are then aware of the expected Stage Activities throughout the development process and which Evaluation Criteria should be presented.

Such clarity in expectations ensures that progress and success can be measured, building confidence in the technology.

Clearly defined Stage Activities allow investors to ensure they place technology developers in the correct stage of a funding scheme and allow technology developers to focus on what is required now, rather than reaching beyond their financial means or technical capabilities.

This document presents a set of six stages which cover the full path from concept creation to commercial readiness.

The six stages reflect the five stages presented by the IEC (9), with the addition of a Stage 0 (Concept Creation) to provide details of very early stage evaluations (Table 2). Some investors run calls based on “Early”, “Mid” and “Late” stages of technical development. While such stage boundaries can be flexible to suit individual investor needs, overall coverage of the Stage Activities presented in this document is recommended. A suggested correlation between stage approaches is presented in Table 2, based on the means of demonstration and verification used.

Stage	Description	TRL
Stage 0	Concept creation	1
Stage 1	Concept development	2 3
Stage 2	Design optimisation	4
Stage 3	Scaled demonstration	5 6
Stage 4	Commercial-scale single device demonstration	7 8
Stage 5	Commercial-scale array demonstration	9

Early (1-3)
Analytical and numerical models

Mid (3-6)
Experimental tests in controlled environment

Late (6-9)
Experimental tests in representative environment

Table 2 Six-stage technology development process

2.2 EVALUATION AREAS

Ten Evaluation Areas are presented in this document as shown below in Figure 5. This list has been developed through an iterative process, building on the outputs of a series of workshops held since 2015 (See Annex A – Preceding Activity) which engaged participants from across the ocean energy sector. The Evaluation Areas represent the concerns of key stakeholder groups, including public and private investors and technology developers, all of whom were engaged in the process.

While this list of Evaluation Areas is considered complete within the scope of this document, it is recognised that additional Evaluation Areas may be necessary in some circumstances. This recognises the evolving nature of the ocean energy sector, emerging markets as well as changing requirements and regulations.

The 2nd Edition of this document added Environmental Acceptabiity, which is a key consideration of technology development and an example of this document evolving based on user feedback.

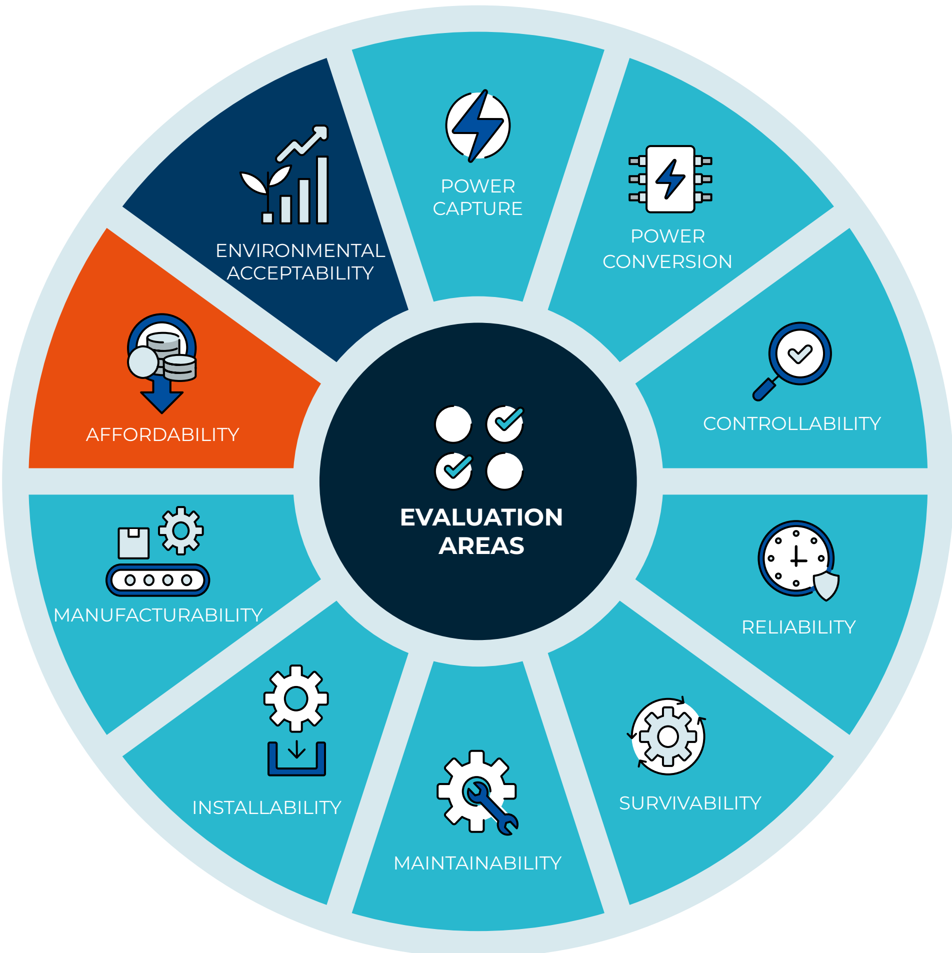


Figure 5 Evaluation Areas included in the Evaluation and Guidance Framework (10)

Full definitions of each of the Evaluation Area, along with their associated Evaluation Criteria are provided in section 3. The definitions are summarised in Table 3.

Evaluation Area	Definition
Power Capture	Power Capture is the process of extracting energy from the natural resource by the interaction with a device and making it available as an input to a power take-off (PTO).
Power Conversion	Power Conversion represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity.
Controllability	Controllability is defined as the ability for control systems to be implemented to a subsystem or device and incorporates evaluation of the benefits control can deliver and the reliance of a subsystem or device on it.
Reliability	Reliability is defined as the "probability that an item can perform a necessary function under given conditions for a given time interval".
Survivability	Survivability is a measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event have passed.
Maintainability	Maintainability is defined as the "ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance".
Installability	Installability is defined as is the ease with which a component, subsystem or device can be prepared, deployed at the operational open-water site and commissioned, resulting in a condition of operational readiness. Installability also includes the ease with which the component, subsystem or device can be recovered.
Manufacturability	Manufacturability is defined as the ability for the technology to be manufactured quickly, cheaply and with minimum waste, and therefore its compatibility with the supply chain's capability, readiness and maturity.
Affordability	Evaluation of Affordability relates to the cost of electricity generated from the wave or tidal stream resource.
Environmental Acceptability	Environmental acceptability can be defined as the ability to make effective use of natural resources, reduce the risks and harms to the operating environment, comply with the relevant regulations, and generate induced benefits whenever possible.

Table 3 Evaluation Area definitions

As described in section 2.3, the rest of the evaluation areas influence Affordability and Sustainability and subsequently the Commercial Attractiveness of a technology. In the hierarchy of evaluation areas, Affordability and Sustainability are at the highest level for the following reasons:

1. All other Evaluation Areas impact Affordability and most influence Sustainability
2. Affordability and Sustainability drive the likelihood of ocean energy forming a significant part of the global electricity generation system.

As such, the next section discusses how the Evaluation Areas are integrated in support of a holistic evaluation of Commercial Attractiveness.

LHD Tidal Current Energy Demonstration project, Xiushan Island, China
Courtesy: LHD

2.3 EVALUATION AREA INTEGRATION

This document considers the Evaluation Areas (Figure 5) separately and defines Evaluation Criteria that can be evaluated in isolation from those of other Evaluation Areas. To bring these together and implement them as part of a holistic evaluation, a process of integration is required. This integration can be illustrated as a hierarchy, similar to that presented in Figure 1, where the Evaluation Areas that are generic to ocean energy technologies provide the inputs to Evaluation Areas that are generic to the energy sector or beyond.

Figure 6 presents the hierarchy of the Evaluation Areas resulting in evaluation of Affordability. This shows the basic groupings of Evaluation Areas and flows of information between these groups; however, it is recognised that the links are considerably more complex than can be represented here. Figure 6 also introduces some parameters which form steps of the integration process, including some which are out of scope of the present document, which focuses on immediate technology-related evaluation.

It is expected that Technical Specifications, standards and protocols will be developed (where they do not already exist) to add detail to the implementation of this integration, see section 3.11.

Controllability and Maintainability appear twice in Figure 6 as the characteristics they represent can impact both the electrical generation performance of a technology and the Operations and Maintenance (O&M) activities required to support it.

Figure 7 presents a simplified version of the integration hierarchy, with Evaluation Area groups shown alongside wider evaluation considerations to illustrate the scope of this document. Technical and process effectiveness considerations form a representation of a technology's system effectiveness, which, when balanced against costs, provide an assessment of the Affordability of a technology. The 2nd Edition of this document begins to approach the consideration of sustainability by including the Evaluation Area of Environmental Acceptability. This, along with Social Acceptability (currently out of scope) contributes to the Sustainability of a technology and an overall evaluation of its commercial attractiveness and the likelihood of energy system uptake.

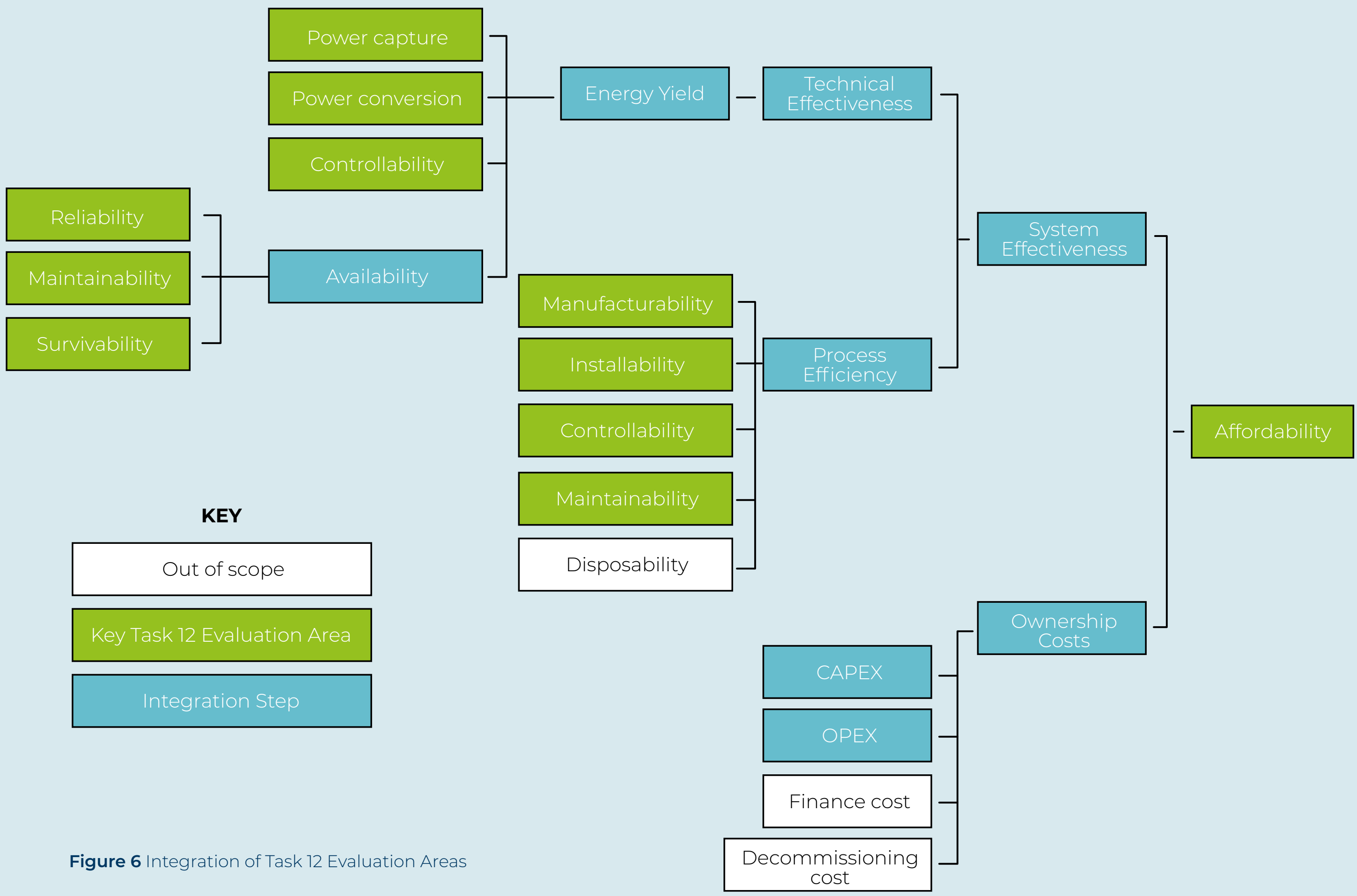


Figure 6 Integration of Task 12 Evaluation Areas

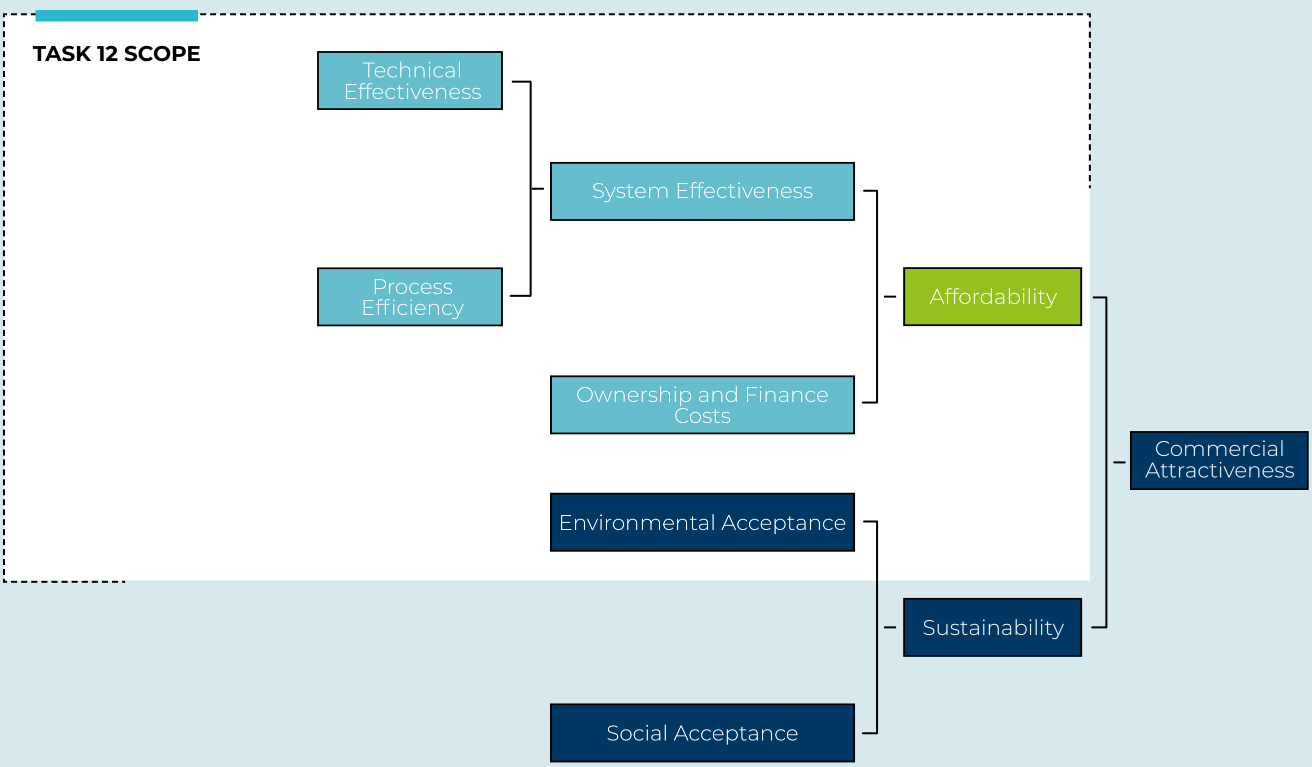


Figure 7 Groups of Evaluation Areas flowing into overall Commercial Attractiveness

Courtesy: Artemis Intelligent Power

3

EVALUATION CRITERIA & STAGE ACTIVITIES

For each Evaluation Area (index in Table 4) this document presents the following:

DEFINITION

- Background context and understanding of the Evaluation Area.

EVALUATION CRITERIA

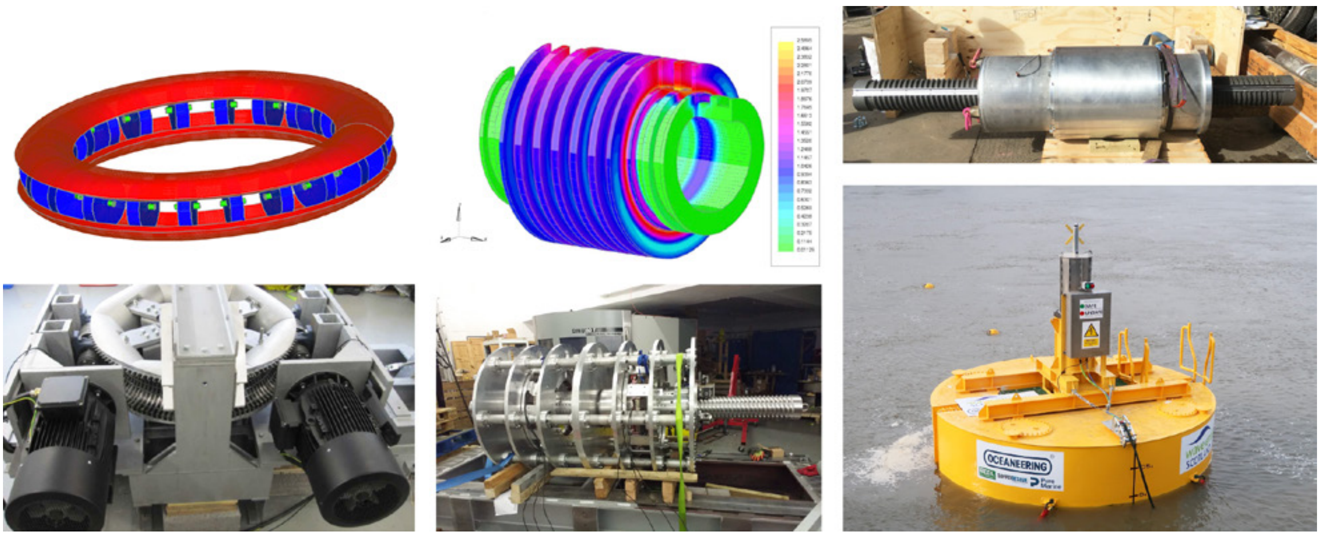
- Definition of the selected criteria and the expected presentation format.
- With the exception of those for Power Capture, all Evaluation Criteria are applicable to wave and tidal stream technology.
- With the exception of Power Conversion, all Evaluation Criteria are applicable to the all levels of aggregation illustrated in Figure 3 (component, subsystem, device and array) within a wave and tidal energy system breakdown.

STAGE ACTIVITIES

- Recommended activities are designed to support the corresponding Evaluation Criteria with the best available knowledge/data, and to ensure that technology development and demonstration activities are robust and appropriate at each stage.
- Further supporting material: where specifically required, technical detail related to an Evaluation Area (or Areas) is provided and referenced within the Stage Activities.

Evaluation Areas	Section, Page
Power Capture	3.1 - page 31
Power Conversion	3.2 – page 41
Controllability	3.3 – page 45
Reliability	3.4 – page 47
Survivability	3.5 – page 50
Maintainability	3.6 – page 55
Installability	3.7 – page 59
Manufacturability	3.8 – page 63
Affordability	3.9 – page 65
Environmental Acceptability	3.9 – page 70

Table 4 Evaluation Areas included in the Evaluation and Guidance Framework



Oceaneering Power-Take-Off Courtesy: Oceaneering, Bathwick Electrical Design Ltd (BEDL), Supply Design Ltd, Pure Marine Gen, Applied Renewables Research and WES

3.1
POWER CAPTURE

3.1.1 DEFINITION

Power Capture is the process of extracting energy from the natural resource by the interaction with a device and making it available as an input to a power take-off (PTO).

Within this document, Power Capture and Power Conversion are considered as two separate elements of the full conversion from resource to electricity. This allows the hydrodynamic efficiency of a device to be evaluated in a different way to the efficiency of a PTO, facilitating a more detailed and accurate evaluation of each subsystem as well as the integrated complete system.

This separation gives more information to relevant stakeholders to better understand where improvements can be made, either focusing on the device or PTO of the system.

It is noted that within other documents, including the IEC Technical Specifications (11) (12), this separation is not considered, and power performance takes account of the whole conversion chain from resource to electrical output as one step.

The separation of Power Capture and Power Conversion is sometimes necessary, for example when the wave energy converter and power take-off subsystem are developed in separate funding programmes or are evolved from existing technologies. However, this can sometimes lead to misleading evaluations. Just as the sea states (section 3.1.4) are an abstraction of the real ocean environment, the design and testing of separate wave energy converters and power take-off subsystems often does not capture the real-life function of the integrated system. The power transfer between the wave energy device and the PTO is not a one-way process, rather the action of the PTO on the device significantly influences its behaviour and its Energy Capture performance (i.e., the PTO affects the amount of power reflected vs. absorbed by the hydromechanical body). Indeed, the use of a control system to optimise Energy Capture can lead to a very different assessment of the integrated system performance in specific sea states, and falsely promote the qualities of specific device types, relative to optimisation for maximum Energy Conversion - that is to say the optimisation of the fundamental requirement of ocean energy considered in this report: electricity generation.

Funders running programmes to develop Power Capture technologies (wave energy converter devices) and Power Conversion technologies (PTOs) should ensure that funded projects consider the implications of separating these complementary functions in the development process. Considering them together through ‘co-design’ (along with the functional impacts of other subsystems) is potentially an ideal development approach, but one that needs to be facilitated by linking funding programmes or driving industrial engagement between projects.

Power train for Orbital Marine Power's O2-2000
Courtesy: Orbital Marine Power

For wave devices, the step of capturing hydrodynamic energy arises from the incoming wave causing movement of elements of the wave device. Depending on the type of device (13), the movement could be between two solid bodies, between the device and an external body such as a fixed foundation, movement in a volume of air or distortion of a flexible component.

Measurement of this movement may be based on force and velocity, torque and angular velocity, pressure difference and flow rate, or mechanical strain.

Most tidal stream technologies have developed around the idea of water moving a turbine, generally using horizontal-axis, vertical-axis or crossflow turbines. In these cases, the power capture is achieved by the revolution of the turbine rotor caused by interaction between the device and the tidal stream, and the measurement of the mechanical input to the PTO is based on torque and velocity.

The Evaluation Criteria for Power Capture must be applicable to a range of wave and tidal stream device types, therefore enabling fair comparison of different types of technology as part of a holistic evaluation process.

3.1.2 EVALUATION CRITERIA

Evaluation Criteria for Power Capture are presented separately for wave and tidal stream energy due to the obvious difference in the form of hydrodynamic power being absorbed by a wave or tidal stream device.

3.1.2.1 WAVE ENERGY EVALUATION CRITERIA

Evaluation Criteria	Units	Format
Power Capture (hydrodynamic to mechanical PTO input)	kW	Matrix of average power capture in each sea state. Sea states are defined by combinations of significant wave height (H_{mo}) and energy period (T_e), each split into bins (or intervals) along the matrix axes. Example shown in Figure 7.
Capture length	m	Matrix of average capture length in bins (or intervals) of Hmo and Te. Example shown in Figure 8. Capture length is defined as: $Capture\ Length\ (m) = \dfrac{Power\ Capture\ (kW)}{Available\ Power\ (kW/m)}$

Table 5 Evaluation Criteria for Power Capture (wave energy)

Average Power Capture per bin (kW)

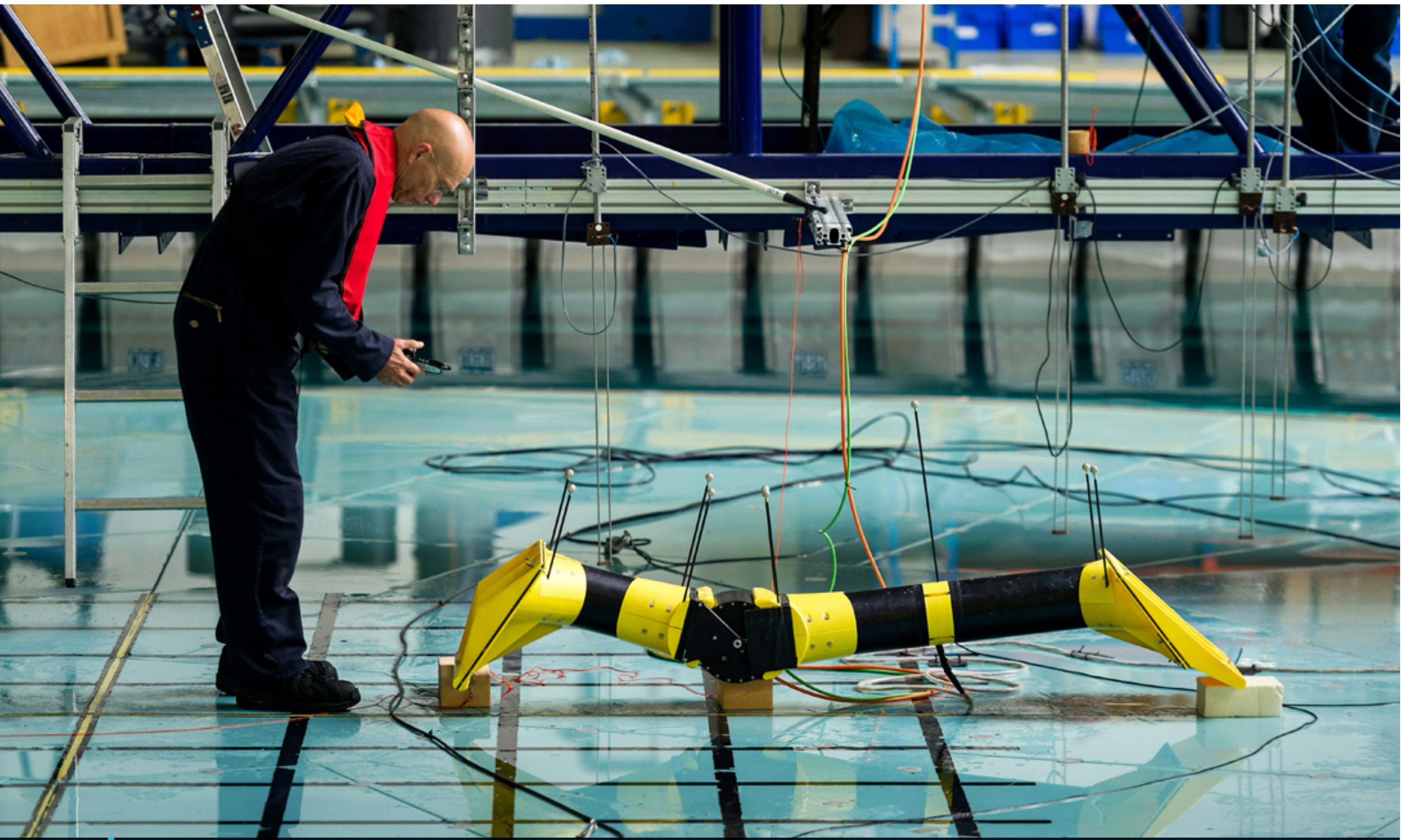
Significant Wave Height Hm0 [m] \ Energy Period Te [s]	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0
7.5																		
7.0													1308.4	1149.3		1200.6		
6.5											1198.7		1267.6	1300.9		1130.6	1007.7	
6.0										1289.1		1280.3	1311.5	1394.7		1174.7	1004.9	
5.5							546.2	999.6	1291.9	1345.1	1289.9	1277.3	1341.5	1205.5	1089.6	850.5	796.1	
5.0							572.8	769.4	1032.3	1260.8	1315.7	1323.1	1251.4	1090.2	875.8	774.5	605.6	
4.5						159.2	366.0	654.8	826.8	1027.4	1131.1	1140.3	1001.0	836.2	728.9	548.5	528.5	
4.0						183.9	306.3	523.0	668.3	803.6	904.0	951.7	804.0	611.5	547.1	489.6		
3.5					36.1	96.3	235.2	396.1	511.9	617.5	695.9	726.3	622.4	519.5	434.8	357.7		
3.0					10.4	81.0	171.2	291.0	365.0	454.2	512.6	526.0	448.4	359.6	321.2		241.8	
2.5					17.0	51.1	122.0	193.4	258.1	317.4	355.5	376.2	314.3	255.2	231.4	184.4	166.8	
2.0				0.6	7.9	35.2	85.8	130.3	166.0	200.2	227.9	237.2	201.4	166.5	139.0	118.0	110.1	
1.5				0.7	5.3	16.4	46.2	71.4	93.5	113.7	128.2	133.8	110.9	92.3	81.0	68.0	63.9	
1.0				0.2	2.1	9.6	19.3	32.2	41.5	50.6	56.7	59.6	50.6		32.4	28.0		
0.5																		

Figure 8 An example power capture matrix – average power capture in each sea state – adapted from (11)

Average Capture Length per bin (m)

Significant Wave Height Hm0 [m] \ Energy Period Te [s]	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0
7.5																		
7.0													3.88	3.15		2.91		
6.5											5.00		4.35	4.14		3.18	2.70	
6.0										7.12		5.65	5.29	5.21	4.10	3.32		
5.5							5.59	8.73	9.73	8.85	7.52	6.71	6.44	5.35	4.53	3.34	2.98	
5.0							7.09	8.13	9.41	10.03	9.28	8.41	7.27	5.86	4.41	3.68	2.74	
4.5						2.90	5.59	8.54	9.30	10.09	9.85	8.94	7.18	5.55	4.53	3.22	2.95	
4.0						4.23	5.93	8.63	9.52	9.99	9.97	9.45	7.29	5.14	4.30	3.64		
3.5					1.34	2.90	5.94	8.54	9.52	10.03	10.02	9.42	7.38	5.70	4.46	3.47		
3.0					0.53	3.32	5.89	8.54	9.24	10.04	10.05	9.28	7.23	5.37	4.49		3.04	
2.5					1.23	3.01	6.04	8.17	9.41	10.10	10.03	9.56	7.30	5.49	4.66	3.51	3.02	
2.0				0.09	0.90	3.24	6.64	8.61	9.45	9.96	10.05	9.42	7.31	5.59	4.37	3.51	3.12	
1.5			0.01	0.20	1.07	2.69	6.35	8.39	9.47	10.06	10.05	9.45	7.16	5.51	4.53	3.59	3.21	
1.0			0.01	0.15	0.97	3.55	5.99	8.51	9.46	10.06	10.00	9.47	7.34		4.07	3.33		
0.5																		

Figure 9 An example capture length matrix – average capture length in each sea state – adapted from (11)



The Mocean wave energy converter scale model
Courtesy: Mocean Energy

3.1.2.2 TIDAL STREAM ENERGY

Evaluation Criteria	Units	Format
Power Capture (hydrodynamic to mechanical PTO input)	kW	Plot of mean power vs. mean current velocity (14). Example in Figure 9.
Power Coefficient	non-dimensional	Plot of mean Power Coefficient, CP (15), vs. mean current velocity. Example in Figure 10. The Power Coefficient is defined as: $C_p = \frac{\text{Power Capture (kW)}}{\text{Available Power (kW)}}$ Where: *Available power = 1/2 ρAU³* ρ = Density of seawater, approimately 1025kg/m³ A = Swept area of the Power Capture device U = Mean current speed (m/s)

Table 6 Evaluation Criteria for Power Capture (tidal stream energy)

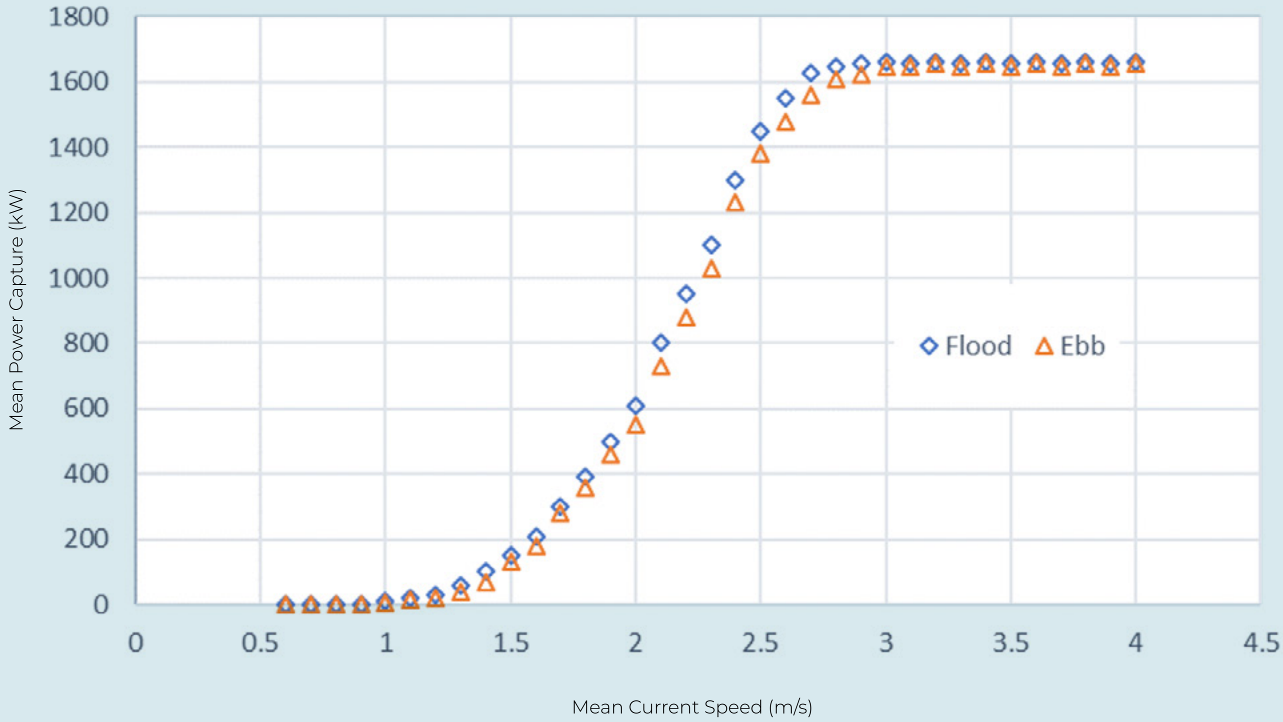


Figure 10 An example of a tidal stream turbine power curve - adapted from (12)

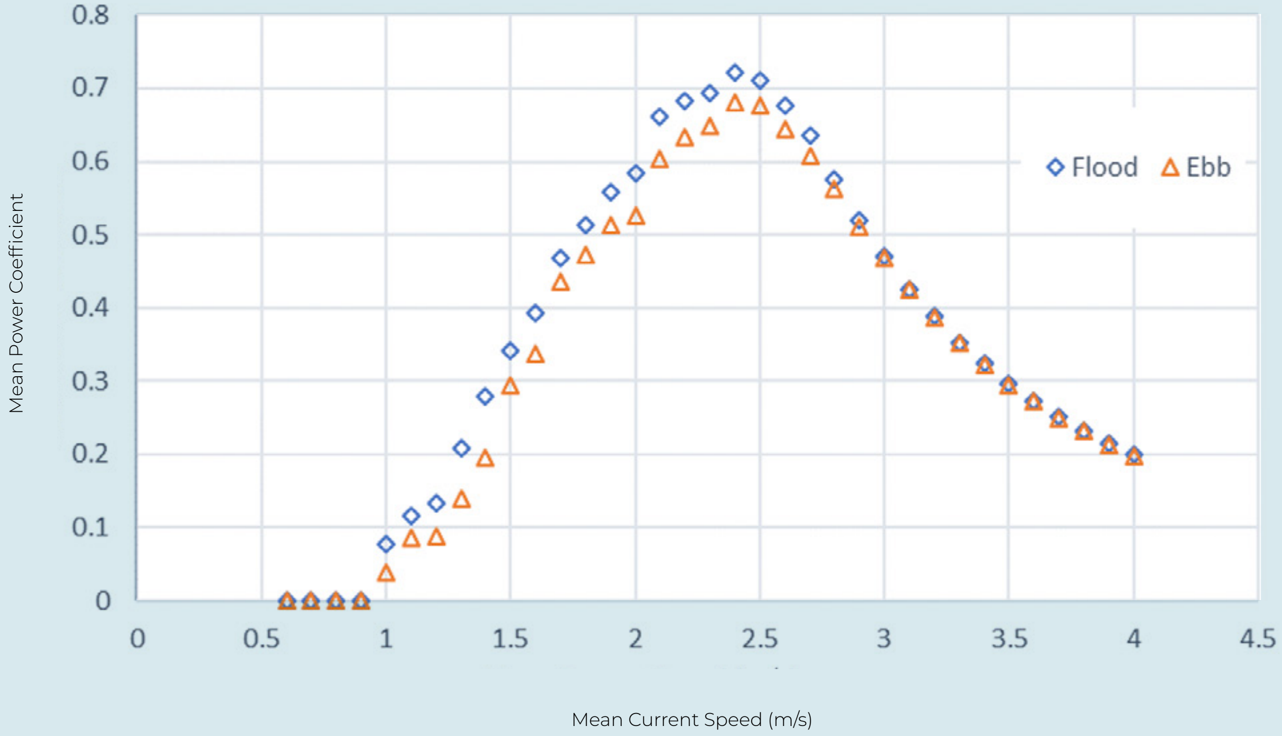


Figure 11 An example of a tidal stream turbine power coefficient curve

3.1.3 STAGE ACTIVITIES

Stage	Stage Activities

Stage 0
Concept creation
	• Definition of technology requirements and challenges associated with Power Capture (the problem statement)
	• Concept definition and identification of physical/ functional characteristics and fundamental operating principles of the device, including:
	  • low/ medium/ high energy resource suitability
	  • deep/ shallow water
	  • floating/ surface piercing/ bottom mounted
	  • likely commercial-scale geometric size of the technology
	  • mode of power capture, degrees of freedom and reaction mechanism for power capture
	  • suitability for implementation of control systems to maximise performance
	  • potential benefits of control systems in terms of operating principles
	  • degree of reliance on control systems to achieve functionality
	• Basic estimates of hydrodynamic power capture based on fundamental relationships between physical parameters (such as swept area or diameter), power production of comparable technologies or fundamental limits (e.g. Betz or Budal limit)
	• Simple capture length ratio (wave) or power coefficient (tidal stream) calculations based on comparable technologies or consideration of fundamental limits (e.g. Betz or Budal limit)

Stage 1
Concept development
	• Evaluation of physical and functional behaviours observed in tank testing conditions which can inform the characterisation of the device power capture functionality and suitability for the expected range of operating conditions
	• Development of a numerical model, to estimate commercial-scale power capture performance
	• Tank testing of device at approximately 1:50 - 1:20 scale (see section 3.1.4.1 for discussion on device scale and size) with appropriate methods to mimic the behaviour of a real PTO, covering:
	  • a range of sea states (see section 3.1.4.2 for a set of recommended wave energy sea states) or currents which provide scaled representation of the target commercial operating conditions to characterise the functional performance
	  • where appropriate, variation of controllable parameters, such as damping or device geometry and evaluation of the impact on power capture performance
	• Validation of the numerical model using tank test data

Stage 2
Design optimisation
	• Further development and refinement of numerical model to estimate commercial-scale power capture performance
	• Tank testing of device at approximately 1:30 - 1:15 scale (see section 3.1.4.1 for discussion on device scale and size) with damping or power take-off method implemented to mimic behaviour of a real PTO, covering:
	  • a range of sea-states (see section 3.1.4.2 for a set of recommended wave energy sea states) or currents which provide scaled representation of the target commercial operating conditions to characterise the functional performance
	  • where appropriate, variation of controllable parameters, such as damping or device geometry and evaluation of the impact on power capture performance
	• Validation of the numerical model using tank test data
	• Engagement with PTO developers to simulate and evaluate the behaviour and performance of the device with integrated PTO

Stage	Stage Activities

Stage 3
Scaled demonstration
	• Further development and refinement of a detailed numerical model to cover full operational envelope, with integrated fully-operational PTO represented
	• Open-water testing (uncontrolled environment) of device at sufficient scale and size to represent commercial-scale performance (1:6 - 1:2 depending on site selection and subsystem size, see section 3.1.4.1 for discussion on device scale and size) with an integrated, fully functional PTO and application of appropriate algorithms to vary controllable parameters, such as damping or device geometry
	• Open-water test campaign of sufficient duration to fully evaluate the device power capture performance through sustained periods of continuous generation in representative conditions:
	  • for wave devices, this is expected to be at least 6 months, depending on the season, to reasonably expect experience of the full range of target energy generation sea-states
	  • for tidal stream devices, this should cover at least one full tidal cycle (spring tide to spring tide or neap to neap)
	• Validation of the numerical model using all available appropriate data.

Stage 4 Commercial-scale single device demonstration	• Further development and refinement of a detailed numerical model with integrated subsystems to cover full operational envelope • Open-water testing (uncontrolled environment) of a single device at commercial scale in a commercially representative site, with fully functional commercial-standard subsystems • Open-water test campaign should be of sufficient duration, with no significant periods of operational interruption, to thoroughly evaluate the device power capture performance. For wave and tidal stream devices, this is expected to be at least 12 months in order to experience the full range of expected operating conditions, taking account of seasonal variations and providing the opportunity to evaluate different system and subsystem settings • Validation of the numerical model using all available appropriate data.
Stage 5 Commercial-scale array demonstration	• Additional numerical modelling and analysis to assess array-related hydrodynamic interaction between devices to reflect the installed array configuration and future array deployments • Selection of array layout based on hydrodynamic modelling and array interaction analysis • Open-water testing (uncontrolled environment) of an array of at least 2 commercial-scale devices[5], in a commercially representative site, with fully functional commercial-standard subsystems • Open-water test campaign should be of sufficient duration, with no significant periods of operational interruption, to evaluate the array power capture performance to a high degree of confidence. For wave and tidal stream devices, this is expected to be at least 2 years in order to experience the full range of operating conditions and build statistical significance of performance characteristics • Ongoing validation of a detailed numerical model with integrated subsystems, to cover the full operational envelope • Validation and ongoing optimisation of any algorithms to vary controllable parameters, such as PTO settings (damping, force or speed restrictions) or device geometry.

Table 7 Stage Activities supporting characterisation and evaluation of Power Capture (wave and tidal stream)

5 The recommendation of "at least 2" commercial-scale devices assumes that each device represents a significant generation capacity (e.g. > 100kW). Novel generation technologies could be aggregations of large numbers of small generation capacity units and the definition of a commercial-scale array should be adapted accordingly

3.1.4 ADDITIONAL GUIDANCE – WAVE ENERGY

This section provides additional guidance on the selection of size and scale for wave energy models or devices and selection of wave conditions for use in Power Capture tank tests. This guidance is intended to assist interactions between public or private investors and technology developers, providing further clarity on the Stage Activities recommended in section 3.1.3.

Partial design consensus has been achieved in the tidal stream technology development. This has not occurred in wave energy technology, with a much larger number and variety of wave energy devices and associated subsystems at various stage of development. Due to this difference in sector maturity, this additional guidance is only considered necessary for wave energy technology development.

3.1.4.1 DISCUSSION ON SIZE AND SCALE WAVE ENERGY OF MODELS AND DEVICES

Model and prototype testing and demonstration is carried out at various reduced scales or sizes during the technology development process, to validate assumptions and maximise cost-effectiveness:

- **Maximising**
  - Learning
  - Risk reduction
  - Confidence building
  - Experience generation
  - Where appropriate, revenue generation
- **While minimising**
  - Safety risk
  - Cost
  - Technical risk

The scale or size must be appropriate to the parameters and characteristics being investigated and measured, but first, the importance of scale vs. size must be clearly defined:

- Scale – ratio of the model size to commercial-scale size
- Size – the physical dimensions of the device

Scale considerations:

- "What constitutes commercial-scale?" - a technology development trajectory could reasonably target numerous product sizes to address different markets
- The ability to scale the impact of natural parameters such as water density
- The impact of functional parameters that scale differently to the main functional charateristics of a device e.g. air pressure and material properties

Size considerations:

- The ability to integrate or otherwise represent a functional subsystem in a particular scale or size of device e.g. the size of a PTO and the size or force-generation capability of a model or actuator used to mimic such a PTO
- The ability to demonstrate an operation or process in a manner representative of commercial-scale e.g. installation or maintenance actions
- The ability of the particular technology to be built or function at smaller size
- The accuracy of extrapolating test results from a small scale to commercial scale
- The availability of appropriate sensing methods and instrumentation equipment to measure the parameter of interest with required accuracy

Considerations affecting both scale and size:

- For tank testing;
  - the water depth of the facility
  - the wave and current generation capability
- In the case of open-water deployment,
  - the ability to find a site with water depth and wave conditions which are comparable, at scale, to the selected commercial-scale including the expectation for extreme waves at the site during deployment

3.1.4.2 SEA STATES FOR POWER CAPTURE EVALUATION OF WAVE ENERGY CONVERTERS

To facilitate objective comparison of wave devices during tank testing, a set of recommended performance tests using a standardised set of sea states has been defined. These should be used in addition to sea states required to satisfy the developers own test objectives.

The sea states presented are representative of wave climates at several test centres, which would be expected to be utilised for the initial demonstrations of a first-of-a-kind commercial-scale system by developers considering grid-scale electricity generation. Public and private investors and developers of wave energy generation technologies for other target markets, and therefore potentially other scales/sizes, may wish to adapt their testing sea states to better represent their target site. As wave energy deployment is being pursued in many global locations with varying levels of energy resource, developers and investors can focus on the sea states most appropriate to their site of interest, while supporting evaluation of the full set of sea states for technology comparison purposes.

The sea states are defined at full scale (see section 3.1.4.1 for discussion on device size and scale) and should be scaled using the appropriate methodology for the type of device.

Industry best-practice should be used for all physical test and demonstration activities (9).

STANDARDISED SEA STATES

Regular Wave Tank Tests

Recommended regular sea states are presented in Table 8.

The duration of a regular sea state test shall be such that 50 - 100 wave cycles are recorded once start-up transients have decayed and the sea state is fully developed at the model location. An appropriate tank settling time should be allowed between tests as advised by the facility operator.

Many wave energy converters have an inherent 'directionality' based on how the device is oriented to the predominant wave direction.

While not listed here, it is recommended that regular wave tests are carried out at several different angles to test the response of the device to a variety of wave directions. The tank test facility and the arrangement of the scaled model and associated infrastructure in the test tank will influence which wave directions are feasible.

For quality control purposes, and to quantify uncertainty or measurement errors, it is important that 'repeatability' tests are carried out at regular intervals during the tank testing. These should be done at the start and end of each day, and between changes to the model configuration.

Two recommended sea states for repeatability tests are R02 and R10 from Table 8.

Sea State ID	T [sec]	H [m]	Direction
R01	5.5	1.5	0°
R02	6.5	1.5	0°
R03	7.5	1.5	0°
R04	8.5	1.5	0°
R05	9.5	1.5	0°
R06	10.5	1.5	0°
R07	7.5	2.5	0°
R08	6.5	3.5	0°
R09	7.5	3.5	0°
R10	8.5	3.5	0°
R11	7.5	4.5	0°

Table 8 Recommended regular sea states for tank testing

Irregular Wave Tank Tests

Recommended irregular sea states are presented in Table 9.

The duration of an irregular sea state test should be such that the following minimum wave cycles are recorded once start-up transients have decayed and the sea state is fully developed at the model location:

- 250 waves (long crested irregular sea states)
- 1500 waves (short-crested irregular sea states).

An appropriate settling time should be allowed between tests as advised by the facility operator.

As discussed for regular waves, it is recommended that some irregular wave tests are carried out at a number of different angles to test the response of the device to a variety of wave directions. The recommended sea states are presented in Table 10.

Sea State ID	T_e [sec]	H_{m0} [m]	γ [6]	θm [7]	s [8]
IR01	6.6	1.5	1.0	0°	∞
IR02	9.0	1.5	1.0	0°	∞
IR03	11.4	1.5	1.0	0°	∞
IR04	12.6	1.5	1.0	0°	∞
IR05	7.8	2.0	1.0	0°	∞
IR06	6.6	2.5	1.0	0°	∞
IR07	9.0	2.5	1.0	0°	∞
IR08	7.8	3.5	1.0	0°	∞
IR09	9.0	4.5	1.0	0°	∞
IR10	10.2	4.5	1.0	0°	∞
IR11	11.4	3.5	1.0	0°	∞
IR12	9.0	3.5	1.0	0°	∞
IR13	7.0	2.5	3.3	0°	6.0
IR14	9.5	3.5	3.3	0°	6.0
IR15	10.7	4.5	3.3	0°	6.0
IR16	9.5	3.5	3.3	0°	10.0
IR17	10.7	4.5	3.3	0°	10.0

Table 9 Recommended irregular sea states for controlled tank testing

Sea State ID	T_e [sec]	H_{m0} [m]	γ	θm	s
IR06b	6.6	2.5	1.0	10°	∞
IR06c	6.6	2.5	1.0	30°	∞
IR08b	7.8	3.5	1.0	10°	∞
IR08c	7.8	3.5	1.0	30°	∞

Table 10 Recommended off-angle irregular sea states for tank testing

6 JONSWAP spectrum enhancement factor
7 Mean wave direction
8 Spreading factor in directional distribution function, $\cos^{2s}[(\theta - \theta_m)/2]$

3.2
POWER CONVERSION

3.2.1 DEFINITION

Power Conversion represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity.

The separation of Power Capture and Power Conversion enables evaluation of the power conversion technology in isolation from the device, either in modelling or rig testing. It is noted that the power capture and power conversion functions are coupled by the damping influence of the PTO on the dynamics of the device, however individual evaluation is necessary to support the (initially) separate development processes.

While this ability to separate Power Capture and Power Conversion is clear for the traditional technical solutions, such as PTOs incorporating hydraulic systems, gearboxes or linear generators, it is less so for more novel technologies. In technologies such as dielectric elastomeric generators (DEGs), and other electro-active-material solutions, the coupling of power capture and power conversion extends further with both functions being carried out by the same component. However, in all cases it is possible to consider the processes separately, and to characterise the form of power transferred between the processes (PTO input) in the appropriate manner, e.g. force and velocity, torque and angular velocity, pressure difference and flow rate, mechanical strain (of DEGs), etc.

While all these forms of power are relevant to wave energy technologies, the mechanical power captured by tidal stream devices, and input to PTOs, is typically (but not always) characterised by torque and angular velocity.

It should be noted that Power Capture and Power Conversion are considered a single *Power Performance* step (as overall wave-to-wire or current-to-wire efficiencies) in the IEC Technical Specifications (11) (12). At later stages of development, when PTOs are integrated with commercial scale power capture devices, the evaluations can be combined in alignment with the IEC process.

3.2.2 EVALUATION CRITERIA

The criterion for Power Conversion, presented in Table 11, is generic to all PTO technologies where the process of converting to electricity can be separated from the process of capturing hydrodynamic energy.

Waveroller Power-Take-Off (PTO)
Courtesy: AW-Energy

Evaluation Criteria	Units	Format
Power Conversion Efficiency	Non-dimensional	Matrix or surface-plot vs. appropriate PTO input power characterisation parameters (e.g. force and velocity, torque and angular velocity, pressure difference and flow rate, mechanical strain) including representation of different damping settings. Power Conversion Efficiency is a measure of the electrical power output divided by the power input to the power take-off $\text{Conversion efficiency, } \eta = \dfrac{\text{Electrical power out (kW)}}{\text{Power at PTO input (kW)}}$

Table 11 Evaluation Criteria for Power Conversion (wave and tidal stream)

Electrical power out is defined as follows:

- Grid-compliant electricity[9], although this can be sub-divided, if required, to provide transparency or to support array design and optimisation, for example:
  1. PTO input power to unconditioned electrical power, e.g. where power is conditioned after aggregation from multiple devices
  2. Unconditioned electrical power to grid-compliant electrical power, including the power conditioning and any associated losses
- It excludes transmission losses from:
  - the electricity generation location to the point of power conditioning to produce grid-compliant electricity, or
  - from the point of grid-compliant electricity production to the point of grid connection, ensuring the measurement is not site specific.

9 A definition of 'grid compliant' for the UK National Grid is in The Grid Code (23), however, the appropriate national definition should be sought by individual users.

3.2.3 STAGE ACTIVITIES

Stage	Stage Activities

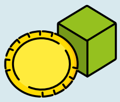
Stage 0
Concept creation
	• Definition of technology requirements and challenges associated with Power Conversion (the problem statement)
	• Concept definition and identification of physical/ functional characteristics and fundamental operating principles of PTO, including:
	  • suitability of the PTO to the fundamental operating principle and force of damping requirements of existing devices
	  • suitability for implementation of control systems to maximise performance
	  • potential benefits of control systems
	  • degree of reliance on control systems to achieve functionality
	• Energy transformation behaviour and efficiency expectations defined based on (or derived from) existing, more mature technologies

Stage 1
Concept development
	• Development of a numerical model to estimate commercial-scale Power Conversion efficiency and validation against test data
	• Physical, laboratory or bench testing of main components or subsystems at an appropriate scale to represent the functional behaviour of the PTO and provide proof-of-concept of the technology, covering:
	  • a representative range of PTO input conditions
	  • representation of inertia and other device-related phenomena
	  • where appropriate, variation of controllable parameters, such as damping
	  • assessment of potential benefits of control system implementation and reliance upon it

Stage 2
Design optimisation
	• Development of a numerical model to estimate commercial-scale power conversion efficiency
	• Physical, laboratory or bench testing of complete PTO subsystem at an appropriate scale to represent the functional behaviour of the PTO technology (see section 3.1.4.1 for discussion on device scale and size), ideally covering:
	  • full range of PTO input conditions, including extremes and representation of inertia and other device-related phenomena
	  • complete characterisation of PTO functional performance including, where appropriate, variation of controllable parameters, such as damping
	  • assessment of potential benefits of control system implementation and reliance upon it
	• Validation of the numerical model using test data
	• Engagement with developers to simulate and evaluate the performance of the PTO subsystem in a device

Stage 3
Scaled demonstration
	• Development of a complete numerical model to calculate commercial-scale Power Conversion efficiency, both in isolation (rig-conditions) and integrated in a device
	• Physical laboratory or rig testing of complete PTO subsystem at sufficient scale to represent commercial-scale performance (see section 3.1.4.1 for discussion on device scale and size), in readiness for integration with a device, covering:
	  • full range of PTO input conditions, including extremes and representation of inertia and other device-related phenomena
	  • demonstration of operational characteristics of PTO functional performance including, where appropriate, variation of controllable parameters, such as damping
	  • assessment of potential benefits of control system to improve performance implementation and reliance upon it
	• Validation of the numerical model using test data

Stage	Stage Activities

 **Stage 4** Commercial-scale single device demonstration	• Development of a complete, integrated numerical model to represent commercial-scale energy transformation performance across a range of input conditions and PTO settings
	• Physical testing of commercial-scale PTO subsystem, covering:
	  • full range of PTO input conditions, including extremes and representation of inertia and other device-related phenomena
	  • complete characterisation of PTO functional performance including, where appropriate, variation of controllable parameters, such as damping
	• Integration of the commercial PTO subsystem with a commercial-scale device
	• Open-water test campaign of sufficient duration, with no signficant periods of operational interruption, to evaluate the Power Conversion efficiency of the PTO to a high degree of confidence. For wave and tidal stream PTOs, this is expected to be at least 12 months in order to experience the full range of expected operating conditions (device, PTO input operating conditions and PTO settings) and to demonstrate sustained performance over an extended duration
	• Validation of the numerical model using rig and open-water test data

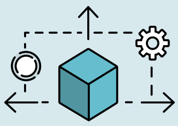
 **Stage 5** Commercial-scale array demonstration	• Integration of the commercial PTO subsystem to an array of at least 2 commercial scale devices in intended commercial deployment conditions • Open-water test campaign of sufficient duration, with no significant periods of operational interruption, to evaluate the PTO's Power Conversion efficiency to a high degree of confidence. For wave and tidal stream PTOs, this is expected to be at least 2 years in order to experience the full range of expected operating conditions (device, PTO input operating conditions and PTO settings) and build statistical significance of performance characteristics and demonstrate sustained performance over a long duration • Full validation of detailed numerical model of the PTO, integrated with the device hydrodynamic numerical model

Table 12 Stage activities supporting characterisation and evaluation of Power Conversion (wave and tidal stream)

3.3 CONTROLLABILITY

3.3.1 DEFINITION

Controllability is defined as the ability for control systems to be implemented to a subsystem or device and incorporates evaluation of the benefits control can deliver and the reliance of a subsystem or device on it.

Control systems are valuable additions, and in many cases essential, to the operation of equipment. In the ocean energy sector, they can be valuable tools to also improve the long-term performance of the wave or tidal energy converter, adapting and optimising system settings to changing environmental conditions. Control can operate at several different levels within a device, including second-to-second optimisation, longer-term adjustment and supervisory monitoring.

Controllability is evaluated as:

- The reliance on control;
  - To what extent the subsystem, device or array requires the control system to achieve basic/ improved/ optimal functionality and the impact of control system failure.
- The ability for control to be implemented;
  - Whether the required control system input parameters are available
  - To what extent the subsystem, device or array has parameters or characteristics which can be controlled
  - The ability of the subsystem, device or array to implement control commands.
- The impact of control on other Evaluation Areas;
  - What improvement in capability is provided by the control system functionality, assessed through other Evaluation Areas and Criteria.

The scale in Table 13 can be used to qualitatively evaluate these characteristics of the overall Controllability of a technology.

Specific Stage Activities related to Controllability (and control) are incorporated in other Evaluation Areas and distributed in the appropriate sections of this document. Evaluation Areas which can be influenced by control are Power Capture, Power Conversion, Survivability, Reliability, Installability and Maintainability. These activities support the evaluation of the impact of the control system capability on other Evaluation Areas. These have not been included in Table 13 as the impacts may be introduced in various combinations throughout the development process, depending on the specific control requirements of the technology. While it is generally considered that delivering higher-category Controllability will provide benefits, it should be noted that not all technologies will require predictive or optimal control i.e. Category 4 control may be necessary for one technology type to operate or be optimised but unnecessary (or not provide optimum cost-effectiveness) for another.

Category	Descriptor	Criteria
0	None	• Completely passive functionality with characteristics selected for: • As-designed technology characteristics • Expected operating conditions (historic model) • Systems/subsystems have no capability to implement control actions
1	Limited/ adjustable	• Mostly passive functionality, with some control parameters capable of limited adjustment of device characteristics during offline maintenance or development activities, based on: • As-built technology characteristics • Expected operating conditions (historic model) • Systems/subsystems have potential to implement limited control actions, perhaps requiring manual intervention (fixed for all environmental conditions)
2	Dynamic (medium-long timeframe)	• Simple control functionality capable of remote adjustment of device characteristics, adapting to seasonal or day-to-day changes in operating conditions, based on: • As-built device characteristics • Recent resource information (measured) • Systems/subsystems have proven capability to implement control actions
3	Dynamic (short-medium timeframe)	• Improved control functionality capable of autonomous or remote adaptation of device characteristics, periodically adapting to present operating conditions, based on: • Real-time monitoring of device characteristics • Realtime sea-state or tidal current information (measured) • Systems/subsystems have proven capability to implement control actions
4	Predictive	• Advanced control functionality with real-time autonomous adaptation of device characteristics to live environmental conditions (wave by wave, second-by-second), based on: • Real-time technology behaviour (measured and modelled) • Real-time and future environmental conditions (measured and forecast) • Systems/subsystems have proven capability to implement control actions with required rapid response times

Table 13 Categories for evaluation of Controllability

3.4 RELIABILITY

3.4.1 DEFINITION

Reliability is defined as the “probability that an item can perform a necessary function under given conditions for a given time interval” (16)

Some failures (or combinations or failures) will result in the “item” failing to “perform a necessary function”, to a required standard.

However, other failures may result is lesser impact on functionality, and it should therefore be noted that not all failures will require immediate maintenance, this being an operational decision based on a wide range of considerations. These may include evaluation of the technical, economic, safety impact of failures, with some resulting in complete system loss or complete failure to function and others resulting in relatively minor and acceptable degradation in performance.

As part of a Failure Modes and Effects Analysis (FMEA), all known failure modes are identified and evaluated for probability of occurrence and impact on the system-level performance, functionality and risk. When combined with an Operations and Maintenance (O&M) model, the FMEA can be used to evaluate criteria for acceptance of failures (continued operation with degraded functionality) and develop maintenance and repair strategies. The reliability of a system has a direct impact on the frequency of O&M activities, both planned and unplanned, which in turn has a significant impact on both the availability and affordability of a project.

3.4.2 EVALUATION CRITERIA

This document separates Reliability from Maintainability, and therefore MTTF was selected as it excludes the time for repair, return to service, and other events such as inspections and preventive maintenance. When repair is considered separately, through the criterion of Mean Time to Repair (MTTR), these parameters can be combined to calculate Availability:

$$Availability = \frac{MTTF}{(MTTF+MTTR)}$$

Evaluation Criteria	Units	Format
Mean Time to Failure (MTTF)	Hours	Numerical value
Failure Rate (probability of failure per unit time)	Non-dimensional	Numerical value

Table 14 Evaluation Criteria for Reliability (wave and tidal stream)

3.4.3 STAGE ACTIVITIES

Stage	Stage Activities
Stage 0 Concept creation	• Definition of technology and market requirements and challenges associated with Reliability (the problem statement) • Selection of high-level reliability targets, appropriate to the technology • Evaluation of the reliability of comparable technologies and applications. This evaluation should be based on the conceptual understanding of the technology and identification of physical and functional characteristics that impact reliability or the requirement for a specific level of reliability, including: • near/ far from shore • deep/ shallow water • floating/ surface piercing/ bottom mounted • suitability for implementation of supervisory monitoring and control systems • proposed structural material considered, with respect to scale and loading scenarios and suitability for expected environmental conditions • concept mode of operation, moving parts, potential exposure, perceived susceptibility to damage
Stage 1 Concept development	• Development of a numerical model or structural calculations to estimate commercial-scale loads in subsystems and devices (see section 3.1.4.1 for discussion on device scale and size) • Identification of likely design limit states • Identification of structural strength of proposed structural materials and high-level evaluation of safety factors of key structural components • Use of experience from similar technology in a comparable environment and application to identify key failure modes and to estimate failure rates. High-level evaluation of the sufficiency of the identified failure modes and rate. • Evaluation of the potential for control system actions to be implemented and consideration of: • potential benefits to Reliability • level of reliance on control to maintain Reliability
Stage 2 Design optimisation	• Physical, laboratory or bench testing of key components at appropriate scale to evaluate life (or cycles) capability and failure rate • Development of numerical model to estimate structural loads on a commercial-scale device, validated to the extent possible using physical testing • Quantitative assessment of likely loads (including fatigue) on a commercial-scale device in representative conditions (see section 3.1.4.2 for a set of recommended wave energy sea-states) from tank test, rig test and validated numerical modelling • Development of an FMEA based on FEED (Front End Engineering Design) activity for Stage 3 open-water test device, tank-test & modelling data, and Reliability experience from similar technology in a comparable environment and application

Stage	Stage Activities
Stage 3 Scaled demonstration	• Open-water testing (uncontrolled environment) of a device (or subsystems in an open-water test rig e.g. device mounted on a barge) at sufficient scale to represent commercial-scale (1:6 - 1:2, see section 3.1.4.1 for discussion on device scale and size) behaviour and performance with representative subsystems • Open-water test campaign should be of sufficient duration to demonstrate Reliability through sustained periods of continuous operation in representative conditions (i.e. in a operational state) • for wave and tidal stream devices, this is expected to be at least 6 months, depending on the season, to reasonably expect significant recurrence of the full range of target operational and environmental conditions, especially any of particular concern to the key failure modes • Application and evaluation of algorithms to allow variation of controllable parameters, such as damping or power capture geometry, which could provide Reliability benefits through load reduction or mitigation • Application of structural load measurement and monitoring of system failures • Further improvement in the fidelity of numerical models to calculate commercial-scale loads, validated using open-water test data • Development of an FMEA for the technology's commercial-scale system-breakdown, informed by testing and analysis experience • Accelerated life testing at suitable scale and size to evaluate key component, subsystem, or device life (or cycles) capability and failure rates. This work should support the development of (and be coherent with) the FMEA and O&M plan
Stage 4 Commercial-scale single device demonstration	• Open-water testing (uncontrolled environment) of a single commercial-scale device, in a commercially representative site, with fully functional commercial-standard subsystems • Open-water test campaign should be of sufficient duration to demonstrate Reliability through a period of deployment in representative conditions with no significant periods of operational interruption, to generate experience to support FMEA validation • for wave and tidal stream devices, this is expected to be up to 12 months to experience of the full range of target operational and environmental conditions • On-going accelerated life testing at appropriate scale to build confidence in key component, subsystem or device life (or cycles) capability and failure rates • Structural load (in device or subsystems), operational condition, environmental condition and system failure monitoring, combined with further development and validation of numerical structural model to build detail and confidence in FMEA including component, subsystem and device failure modes and failure rates
Stage 5 Commercial-scale array demonstration	• Open-water testing (uncontrolled environment) of an array of at least 2 commercial-scale devices, in a commercially representative site, with fully functional commercial-standard subsystems • Open-water test campaign should be of sufficient duration (at least 2 years) to demonstrate and evaluate Reliability across the full range of operational and environmental conditions. Periods of operational interruption should be minimised, and primarily focussed on general maintenance, to support FMEA validation. • On-going accelerated life testing at appropriate rig scale and size to build confidence in key component, subsystem or device life (or cycles) capability and failure rate • Structural load, operational condition, environmental condition and system failure monitoring, combined with ongoing development and validation of numerical structural model to build detail and confidence of FMEA including component, subsystem, device and array failure modes, failure rates and MTTF • Definition of commercial Reliability management approach, including monitoring, prognostics/diagnostics and any ongoing accelerated life test and management approaches to predict and mitigate future operational interruptions

Table 15 Stage Activities supporting characterisation and evaluation of Reliability (wave and tidal stream)

3.5 SURVIVABILITY

3.5.1 DEFINITION

Survivability is a measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event has passed.

In ocean energy, the 'event' can result from a combination of environmental factors such as wind, wave, current, directionality and temperature which exceed the conditions the subsystem or device has been designed for. In many cases, but not all, these will be based on extreme conditions, or infrequent storm events. Survivability is closely linked with Reliability; however, the focus of Reliability is on ability to continue to perform under given conditions.

Survivability depends on:

- Likelihood of experiencing an event which results in components, subsystems or devices operating beyond their expected design conditions.
- Likelihood of being able to predict or detect the survival event and take suitable protective action.
- Likelihood of resisting the event having taken suitable protective action.
- Likelihood of resisting the event not having taken suitable protective action.

A significant amount of research and design focus is dedicated to satisfying the Survivability requirements of ocean energy technology. Ensuring Survivability requires a design with sufficient and appropriate safety factors as excessive safety factors lead to over-specification of components, subsystems and devices, and a subsequent increase in CAPEX. It is therefore important to understand the specific Survivability requirements of a technology for the given project(s), deployment site(s) and environment(s) to balance survival against excessive increase in CAPEX.

The focus of Survivability within this document is on devices being tested in open-water conditions, in an uncontrolled environment. Such testing increases the probability of events which may cause damage or loss of functionality beyond an acceptable level and can also result in situations where the implications of such damage can be significant. Actions should be taken in the early stages of development to understand these events and their implications, allowing appropriate design decisions to be made where possible. Some of these actions are informed by early stage modelling, testing and analysis, increasing the importance of having access to reliable and validated information. System designs will be adapted iteratively through the development stages, due to continued optimisation of the design conditions as the understanding of the survival events improves and updated analyses of events outside the design conditions become available.

‘Suitable action’ taken as part of the survival strategy can be considered:

- *passive*, with design decisions having reduced risks associated with survival events as low as reasonably practicable, with no further action taken before/during the survival event,or
- *active*, where system features are enabled with the specific purpose of increasing likelihood of survival during these events.

3.5.2 EVALUATION CRITERIA

Two different approaches to presenting the quantitative metrics for Survivability are:

- The limit of design conditions (and associated environmental conditions), beyond which the component, subsystem or device behaviour in survival events is unknown, and damage or loss of functionality may occur
- The likelihood of exceeding an acceptable level of damage or loss of functionality in such an event

The identification of an ‘acceptable level’ will be on a case-by-case basis for each technology or project, taking account of factors including environmental, financial (e.g. repair cost vs. device value) or reputational risks. Such a decision is beyond the scope of this document.

There is often a strong correlation between environmental conditions and design conditions, therefore the limit of design conditions can be calculated as a limit in environmental conditions. For wave energy, based on known device behaviour, the force or velocity limits for a PTO can be calculated as a combination of wave height and period. The expected frequency of occurrence of this combination can be determined from site data and can also be predicated based on weather forecasts. Such prediction allows suitable protective action to be taken to decrease the likelihood of exceeding an acceptable level of damage.

For tidal stream technologies, the limit of design conditions may be calculated as limits in current velocity in combination with change in water depth (lunar cycle, storm surges etc.), turbulence and wave height or direction.

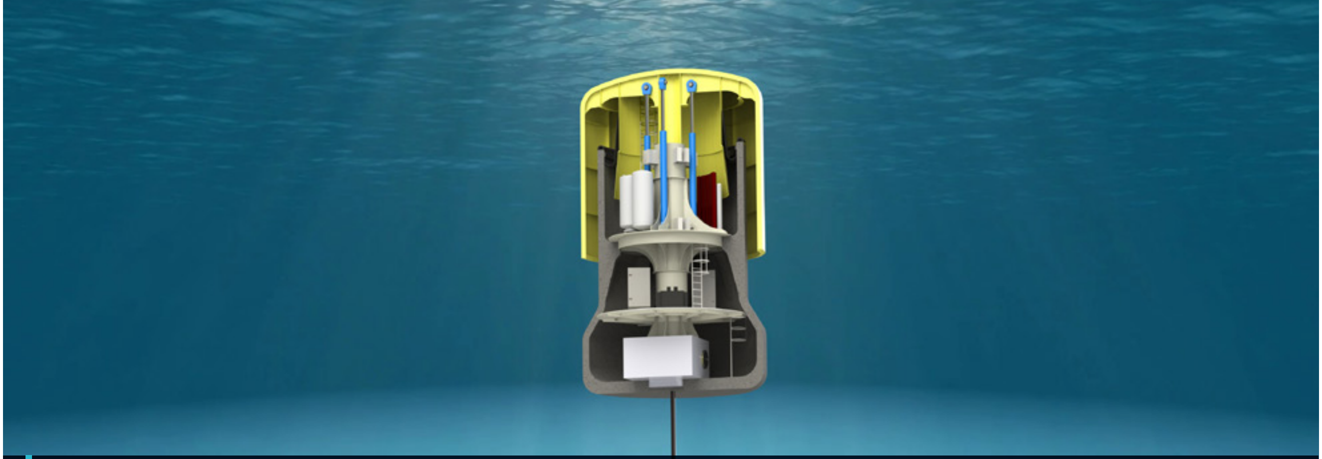
The Design Conditions Boundary describes the most severe input conditions the component, subsystem or device has been designed to survive, described in the appropriate fashion for the specific technology (e.g. PTO force vs velocity), and related to the event(s) that would cause those input conditions.

The Evaluation Criteria will be technology specific, while the likelihood of exceeding acceptable level of damage or loss of functionality will be site specific. Detailed analysis of site data will be required for each project to assess the likelihood of site conditions resulting in exceedance of Design Condition Boundaries. These limits can be presented against expected conditions for a specific site or class of site, or a list of maximum values for different subsystems.

The Evaluation Criteria may also consider the response time for suitable protective action, and the corresponding time to return to a generation mode after the survival event has passed.

Evaluation Criteria	Units	Format
Design Conditions Boundary - beyond which a component, subsystem or device behaviour is unknown, and damage or loss of functionality may occur	Appropriate to component, subsystem or device	Maximum, combination or range of values
Likelihood of exceeding an acceptable level of damage or loss of functionality, with or without taking suitable protective action	Non-dimensional	Numerical value. Calculated probability or likelihood estimate based on best available information

Table 16 Evaluation Criteria for Reliability (wave and tidal stream)



AWS schematic drawing
Courtesy: AWS

3.5.3 STAGE ACTIVITIES

Activities relating to Survivability predominantly occur during the earlier stages while significant design decisions are being made. They focus on understanding the events which may cause damage or loss of functionality for the device and develop means to mitigate these risks. Extensive understanding of the operational requirements at the intended commercial deployment site and open water test sites, as well as environmental conditions and device behaviour are fundamental.

Stage	Stage Activities
Stage 0 Concept creation	• Definition of technology and market requirements and challenges associated with Survivability (the problem statement) • Selection of high-level Survivability targets appropriate to the technology • Evaluation of the Survivability of comparable technologies and applications. This evaluation should be based on the conceptual understanding of the technology and identification of physical and functional characteristics that impact Survivability or the requirement for a specific level of Survivability • Understanding of general deployment site environmental conditions • Clear definition of what the survival events may be, and their likely impact on systems • High-level survival strategy definition

Stage 1
Concept development
	• Critical evaluation of physical and functional characteristics of the concept that impact Survivability, including:
	  • modes of operation and any fundamental characteristics that improve the ability to survive extreme conditions
	  • suitability for implementation of protective control and monitoring systems
	• Analysis of prospective site conditions to determine likely events (within design conditions) or unlikely event (beyond design conditions)
	• Clear definition of what the survival events may be, and their likely impact on systems
	• Identification of likely design limit states & identification of structural strength of selected structural materials
	• Survival strategy definition, including suitable protective action (active and/or passive)
	• Definition of prediction, detection and alerts systems
	• Development of a numerical model to estimate extreme commercial-scale loads
	• Initial estimation of impact on LCOE of damage or loss of functionality

Stage	Stage Activities
Stage 2 Design optimisation	• Extensive analysis of site conditions to determine what events are likely or unlikely to occur • Review of design condition boundary based on knowledge gained from design work to date • High-level evaluation of safety factors of key structural components • Development of survival strategy including suitable protective action (active and/or passive) • Development of prediction, detection and alerts systems • Definition of actions prior to reinstatement of all normal operations (diagnostic plans, sensor information, safety checks, physical inspection) • Adaption of installation plan, O&M model and FMEA to account for protective action • Dedicated tank or rig testing to examine subsystem/device behaviour during survival events • Dedicated numerical model(s) suitable for analysing survival events and extreme environmental conditions • Validation of numerical model using data available • Measurement of key structural and pressure loads in device • Estimate of impact on LCOE of damage or loss of functionality and implementation of protective action (cost of required systems and reduced availability) supported by outputs of modelling, testing and design
Stage 3 Scaled demonstration	• Extensive analysis of site conditions to determine what events are likely or unlikely to occur, including combinations of environmental conditions (wind, wave, current etc.) • Analysis of seasonal variability and extreme conditions at site • Review of Design Condition Boundary based on knowledge gained to date • Development of an FMEA for the technology's commercial-scale system-breakdown, informed by testing and analysis experience • Development of process for reinstatement of all normal operations following survival event • Adaptation of installation plan, O&M model and FMEA to account for protective action • Demonstration and evaluation of the effectiveness and reliability of survival strategies, including failsafe modes and algorithms to control protective action(s) during testing at sufficient scale to represent commercial-scale device (see section 3.1.4.1) • Further development of increased complexity numerical model to calculate commercial-scale loads and safety factors in survival events • Dedicated tank or rig testing to examine component, subsystem or device behaviour and loading during survival events, expanding the range of conditions used for the testing • Validation of numerical model using data available from physical testing and any other appropriate available data • Calculation of impact on LCOE of damage or loss of functionality and implementation of protective action (cost of required systems and reduced availability)

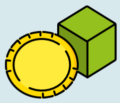
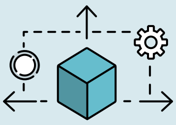
Stage	Stage Activities
 **Stage 4** Commercial-scale single device demonstration	• Ongoing survival and extreme load analysis, taking account of component reliability and fatigue as components/subsystems age • Update installation plan, O&M model, FMEA based on open water testing experience • Update analysis of site conditions to determine what events are likely or unlikely to occur including combinations of environmental conditions (wind, wave, current etc.) • Review of Design Condition Boundary based on knowledge gained to date • Demonstration and evaluation of survival strategies on a commercial-scale device, including failsafe modes ad algorithms to control variable parameters, such as damping or Power Capture geometry, or other active protective actions • Test of prediction, monitoring, detection and alerts systems • Update of survival strategy and protective action based on Reliability assessments • Further development of numerical model taking account of deployment experience and updated FMEA • Continued tank testing and rig testing at a scale and size sufficient for representation of survival events and extreme conditions • Update to LCOE based on available survival test and modelling data
 **Stage 5** Commercial-scale array demonstration	• Update analysis of site conditions to determine likely events (within design conditions) or unlikely event (beyond design conditions), based on updated understanding of device • Structural load measurement and monitoring of system failures • Ongoing monitoring of system functionality along with Reliability actions, with update made to survival strategy if required • Ongoing use and development of prediction, monitoring, detection and alerts systems • Refinement and use of numerical model taking account of deployment experience and updated FMEA • Update to LCOE based on available survival test and modelling data, taking account of damage or loss of functionality, and implementation of protective action (cost of required systems and reduced availability)

Table 17 Stage Activities supporting characterisation and evaluation of Survivability (wave and tidal stream)

3.6 MAINTAINABILITY

3.6.1 DEFINITION

Maintainability is defined as the "ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance". (17)

The "ability" is driven by several considerations, both technological and process related:

- The characteristics of a technology and its inherent need for maintenance – linked to Reliability
- The action required to maintain (through planned or unplanned maintenance, including modification, adjustment, repair or replacement)
- The range of environmental conditions required to allow maintenance action to be completed
- The location where the maintenance action can be carried out, driven by logistical considerations such as access and availability of infrstructure
  - in-situ (in defined environmental conditions)
  - in an offshore location with higher likelihood of experiencing defined environmental conditions i.e. in a sheltered bay or on a vessel
  - in port
  - onshore (on quayside or onshore maintenance facility)
- The time taken to carry out the action and return to full operation

Alongside the "ability" for maintenance to be carried out, the cost of maintenance must be considered as a contributor to OPEX.

3.6.2 EVALUATION CRITERIA

The Evaluation Criteria for Maintainability show a clear similarity to those defined for Installability.

Evaluation Criteria	Units	Format
Range of acceptable environmental conditions Wave height – H_{m0} and H_{max} Wave period – T_e Wind speed – U_{10} Tidal current Tidal range or tidal water depth	m s m/s m/s or kt m	Numerical values, upper and lower limits or combinations of conditions
Mean Time to Repair (MTTR, or to maintain) Measure of the time from the start of maintenance - when all resources are available and environmental conditions are within limits - until the system is returned to operation. Mobilisation and transit to site are excluded to remain site independent.	Hours	Numerical values (with **minimum and maximum** to quantify variance and its impact on availability)
Cost to Repair (or maintain) Includes all costs of maintenance and re-commissioning e.g. vessels to access a device, tow a device to maintenance location (if required), labour and specialist staff or equipment.	£, € or $	Numerical values (**minimum and maximum** to quantify variance and its impact on cost)

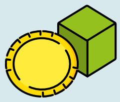
Table 18 Evaluation Criteria for Maintainability (wave and tidal stream)

3.6.3 STAGE ACTIVITIES

Stage	Stage Activities
Stage 0 Concept creation	• Definition of technology and market requirements and challenges associated with Reliability (the problem statement) • Selection of high-level Maintainability targets appropriate to the technology • Evaluation of the Maintainability of comparable technologies in similar applications and environmental conditions. This evaluation should be based on the conceptual understanding of the technology and identification of physical and functional characteristics that impact Maintainability, including: • access restrictions for device (water depth and installation type) • likely accessibility, modularity and transportability of components and subsystems • suitability for maintenance operations on-site or in a protected location (harbour) • potential distance from port • environmental conditions at prospective type of site • identifiable Health, Safety and Environment (HSE) risks

Stage	Stage Activities
Stage 1 Concept development	• Evaluation of the Maintainability characteristics of the technology, including: • component Operations and Maintenance (O&M) guidance/recommendations • access restrictions for device (water depth and installation type) • likely accessibility, modularity and transportability of components and subsystems • suitability for maintenance operations on-site or in a protected location (harbour) • potential distance from port • environmental conditions at prospective type of site • identifiable Health, Safety and Environment (HSE) risks • Development of a high-level O&M process including likely planned maintenance activities in response to: • the identification of key failure modes based on experience from wider application of similar technology and assessment of which parts of the system will require maintenance, can be repaired or require replacement • HSE processes arising from identification of HSE risks
Stage 2 Design optimisation	• Optimisation of the technology in response to the fundamental Maintainability characteristics, including: • access restrictions for device (water depth and installation type) • likely accessibility, modularity and transportability of components and subsystems • suitability for maintenance operations on-site or in a protected location (harbour) • potential distance from port • environmental conditions at intended type of site • Development of an initial O&M model including: • failure modes from FMEA • simulation of: · environmental conditions · vessel and other infrastructure availability, capability and cost data · duration of maintenance actions, and estimates of component replacement cost and availability · marine operations limitations and restrictions • HSE processes arising from identification of HSE risks • Use of O&M model to guide system design optimisation
Stage 3 Scaled demonstration	• Development of a complete O&M model and an O&M plan in preparation for open-water deployment, incorporating: • failure modes from FMEA • information from technology fabrication • simulation of: · environmental conditions · vessel and other infrastructure availability, capability and cost data · marine operations limitations and restrictions · planned and unplanned maintenance cost and repair times • Definition of HSE actions to be implemented in the O&M plan • Use of O&M model to guide O&M plan optimisation by identifying the failure modes with greatest impact on cost and availability • Practical demonstration of the O&M plan through operation and maintenance actions during an open-water test programme at sufficient scale to represent commercial-scale marine operations. This is likely to be 1:6 - 1:2 scale.

Stage	Stage Activities


Stage 4
Commercial-scale single device demonstration
	• Update and any required extension of the O&M model and O&M plan in preparation for open-water deployment incorporating:
	  • failure modes from FMEA based on commercial-scale technology design and system breakdown
	  • information from technology fabrication and Stage 3 deployment
	  • simulation of:
	    · environmental conditions
	    · vessel and other infrastructure availability, capability and cost data
	    · marine operations limitations and restrictions
	    · planned and unplanned maintenance cost and repair times
	    · resulting waiting times, predicted O&M activity and system availability
	• Definition of HSE actions to be implemented in the O&M plan
	• Use of O&M model to guide O&M plan optimisation by identifying the failure modes with greatest impact on cost and availability
	• Practical demonstration of the O&M plan through operation and maintenance actions during a 12 month open-water test programme, gaining evidence to validate the model inputs and assumptions.

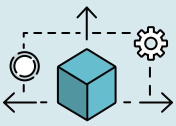

Stage 5
Commercial-scale array demonstration
	• Update and any required extension of the O&M model and O&M plan in preparation for open-water deployment incorporating:
	  • extension to represent array deployment and infrastructure
	  • failure modes from array-level FMEA based on commercial-scale technology design and system breakdown
	  • information from technology fabrication and Stage 4 deployment
	  • planned and unplanned maintenance cost and repair time
	  • simulation of:
	    · environmental conditions
	    · vessel and other infrastructure availability, capability and cost data
	    · marine operations limitations and restrictions
	    · planned and unplanned maintenance cost and repair times
	    · resulting waiting times, predicted O&M activity and system availability
	    · planned and unplanned maintenance cost and repair times
	• Definition of HSE actions to be implemented in the O&M plan
	• Use of O&M model to guide O&M plan optimisation by highlighting key failure modes
	• Practical demonstration of the O&M plan through operation and maintenance actions during a 5-year open-water test programme, gaining evidence to validate the model inputs and assumptions
	• Continuous update of the O&M model and plan based on open-water deployment experience

Table 19 Stage activities supporting characterisation and evaluation of Maintainability (wave and tidal stream)

3.7 INSTALLABILITY

3.7.1 DEFINITION

Installability is defined as the ease with which a component, subsystem or device can be prepared, deployed at the operational open-water site and commissioned, resulting in a condition of operational readiness. Installability also includes the ease with which the component, subsystem or device can be recovered.

Installability is evaluated from two perspectives:

- The environmental conditions required to install the technology
- The time and cost to install, assuming the required environmental conditions are available

These perspectives illustrate the sources of potential improvement available to developers; those that expand the range of installation environmental conditions, and those that reduce time and cost when conditions are available.

Installation cost is estimated to account for circa 10% of the cost of energy of a wave energy project and circa 35% for a tidal stream project (18), with the main drivers identified as:

- Type and availability of vessels required
- Distance to port
- Time taken for installation
- Time waiting on weather conditions

Other considerations which will impact the cost of installation (and recovery) are:

- Mass and size of device
- Use of quick connection system
- Foundation/mooring approach
- Lifting equipment requirement
- Subsea infrastructure connection (or disconnection) requirements
- Reliance on divers and Remotely Operated Vehicles (ROVs)
- Boat transfer method and mooring of support vessels

SMEC Plat-I Installation, Grand Passage, Nova Scotia, Canada
Courtesy: Sustainable Marine Energy (Canada) Ltd. (SMEC)

3.7.2 EVALUATION CRITERIA

The Evaluation Criteria for Installability show a clear similarity to those defined for Maintainability.

Evaluation Criteria	Units	Format
Range of acceptable environmental conditions for installation (or recovery) Wave height – H_{m0} and H_{max} Wave period – T_e Wind speed – U_{10} Tidal current Tidal range or tidal water depth	m s m/s m/s or kt m	Numerical values, upper and lower limits or combinations of conditions
Mean Time to Install (or recover) Measure of the time from the start of installation on-site (or recovery) - when all resources are available and environmental conditions are within limits - until the system is in an operation state. Mobilisation and transit to site are excluded to remain site independent.	Hours	Numerical value (with **minimum and maximum** to quantify variance and its impact on availability)
Transit speed Measure of the likely transit speed of the component, subsystem or device, using the likely transport solution, to evaluate the time to reach the deployment location while allowing other Evaluation Criteria to remain site independent.	knots	Numerical values (**minimum and maximum** to quantify device limits
Cost to Install (or recover) Includes all costs of commissioning e.g. vessels, labour and specialist equipment.	£, € or $	Numerical value (with **minimum and maximum** to quantify variance and its impact on cost)

Table 20 Evaluation Criteria for Installability (wave and tidal stream)

3.7.3 STAGE ACTIVITIES

Stage	Stage Activities

Stage 0
Concept creation
	• Definition of technology and market requirements and challenges associated with Installability (the problem statement)
	• Selection of high-level Installability targets appropriate to the technology
	• Evaluation of the Installability of comparable technologies in similar applications and environmental conditions. This evaluation should be based on the conceptual understanding of the technology and identification of physical and functional characteristics that impact Installability, including:
	  • environmental conditions at prospective type of site
	  • water depth at prospective type of site
	  • device accessibility (e.g. surface piercing/ floating/ bottom mounted)
	  • installation vessel requirements
	  • complexity of marine operations
	  • identifiable Health, Safety and Environment (HSE) risks

Stage 1
Concept development
	• Concept characterisation of Installability characteristics of the technology, including:
	  • environmental conditions at prospective type of site
	  • water depth at prospective type of site
	  • device accessibility (e.g. surface piercing/ floating/ bottom mounted)
	  • installation vessel requirements and transit speed
	  • complexity of marine operations
	  • identifiable Health, Safety and Environment (HSE) risks
	• Development of a high-level installation plan based on the characteristics and scale of the technology. This plan may take the form of a simple storyboard and must consider the HSE implications of the process

Stage 2
Design optimisation
	• Optimisation of fundamental Installability characteristics and development of technical solutions to maximise Installability
	• Evaluation of HSE implications of the installation plan
	• Development of a detailed installation plan including:
	  • vessel requirements (installation vessel, support vessel, ROV)
	  • indication of vessel and equipment costs
	  • consideration of marine operations complexity
	  • definition of desirable installation environmental conditions
	  • detailed storyboard defining the installation process, including on-shore transportation, launch method, transit to deployment site, connection (mooring and electrical) and commissioning
	• Evaluation of HSE implications of the installation plan

Stage 3
Scaled demonstration
	• Development of a complete installation plan in preparation for open-water deployment, including:
	  • port requirements definition and port selection
	  • launch method definition
	  • specification of vessels (installation vessel, support vessel, ROV) with detailed evaluation of vessel and equipment costs
	  • detailed assessment of marine operations feasibility with respect to technology characteristics, specific site conditions, vessel/operator capability and expected environmental conditions

Stage	Stage Activities
Stage 3 Scaled demonstration	• specification of vessel routes from port to deployment site • connection and commissioning process • definition of HSE actions to be implemented in the installation plan • Engagement of competent persons to complete independent review of installation and operations plan • Practical demonstration of the installation plan through installation (and any retrievals/re-installations) during an open-water test programme at sufficient scale and size to represent commercial-scale marine operations. This is likely to be 1:6 - 1:2 scale.

Stage 4
Commercial-scale single device demonstration
	• Adaptation and extension of the installation plan in preparation for commercial-scale open-water deployment, including:
	  • port requirements definition and port selection
	  • launch method definition
	  • specification of vessels (installation vessel, support vessel, ROV) with detailed evaluation of vessel and equipment costs
	  • detailed assessment of marine operations feasibility with respect to technology characteristics, specific site conditions, vessel/operator capability and expected environmental conditions
	  • specification of vessel routes from port to deployment site
	  • connection and commissioning process
	  • definition of HSE actions
	• Engagement of external experts to complete independent review of installation plan
	• Practical demonstration of the installation plan through installation (and any retrievals/re-installations) during an open-water test programme of at least 12-month duration, gaining evidence to validate the plan's inputs and assumptions.

Stage 5
Commercial-scale array demonstration
	• Optimisation of a complete, commercial array-scale installation plan in preparation for open-water deployment including:
	  • ports requirements definition, selection and launch method
	  • specification of vessels (installation vessel, support vessel, ROV) with detailed evaluation of vessel and equipment costs
	  • detailed assessment of marine operations feasibility with respect to commercial technology design, specific site conditions, vessel/operator capability and expected environmental conditions
	  • specification of vessel routes from port to deployment site
	  • connection and commissioning process, including array inter-connections and other array-related infrastructure
	  • Definition of HSE actions
	• Independent review of installation plan
	• Practical demonstration of the installation plan through installation (and any retrievals/re-installations) during an open-water test programme of at least 2 years duration with an array of 2 or more devices, gaining evidence to validate plan's inputs and assumptions.

Table 21 Stage Activities supporting characterisation and evaluation of Installability (wave and tidal stream)

3.8 MANUFACTURABILITY

3.8.1 DEFINITION

Manufacturability is defined as the ability for the technology to be manufactured quickly, cheaply and with minimum waste, and therefore its compatibility with the supply chain's capability, readiness and maturity.

Using the principles of Design for Manufacture ensures that existing design guidelines and recommendations are applied and that the ability to cost-effectively manufacture the technology is considered throughout the design process. Considering manufacturing early in the design process as possible can help avoid complexity and expensive processes, including those which are time inefficient, result in waste material or may pose a health and safety risk.

Evaluation of Manufacturability considers the following aspects of the manufacturing process:

- Novelty of the technology
- Existence and experience of the supply chain and the state-of-the-art
- Material properties and availability
- Complexity of the manufacturing process
- Infrastructure requirement, availability and location
- Large-scale production options (with respect to both technology size and quantity)
- Manufacturing process duration
- Cost

Many of these criteria are either subjective or logistical and should be evaluated by technology developers during the development of relationships with manufacturing contractors.

Information on the cost of a manufacturing process will contribute to the evaluation of Affordability (see section 3.9).

3.8.2 EVALUATION CRITERIA

The Evaluation Criterion for Maintainability is applicable at all levels of aggregation from components to arrays and is summarised in the tables below.

Evaluation Criteria	Units	Format
Manufacturing Readiness Level (MRL) (19)	Non-dimensional	Score of 1-10, see Table 22
Time to manufacture	Hours	Numerical value (with **minimum and maximum** to quantify variance)
Cost to manufacture	£, € or $	Numerical value (with **minimum and maximum** to quantify variance and its impact on cost)

Table 22 Evaluation Criteria for Maintainability (wave and tidal stream)

Phase	MRL	Definition
Material solutions analysis	1	Basic manufacturing implications identified
	2	Manufacturing concepts identified
	3	Manufacturing proof of concept developed
	4	Capability to produce the technology in a laboratory environment.
Technology maturation and risk reduction (formerly "technology development")	5	Capability to produce prototype components in a production relevant environment.
	6	Capability to produce a prototype system or subsystem in a production relevant environment.
Engineering and manufacturing development	7	Capability to produce systems, subsystems or components in a production representative environment.
	8	Pilot line capability demonstrated. Ready to begin low rate production.
Production and Deployment	9	Low rate production demonstrated. Capability in place to begin Full Rate Production.
Operations and Support	10	Full rate production demonstrated and lean production practices in place.

Table 23 Manufacturing Readiness Level definitions (19)

3.8.3 STAGE ACTIVITIES

A detailed set of stage activities have not been presented for Manufacturability. The activity is engrained in the evolution of an increasingly detailed manufacturing plan and the demonstration of that plan through the manufacture of increasing size models and prototypes until commercial scale is achieved.

At early stages, the evaluation of manufacturing requirements relative to the state-of-the-art capability of the manufacturing sector is important. Subsequently, the evaluation is delivered by iterative engagement with potential manufacturing partners who will have the expertise required to determine manufacturing requirements and limitations. Relevant authoritative sources for the manufacturing process or component should be consulted. Staged development of projects will de-risk scale-up of the technology while demonstrating manufacturing feasibility.

Cost and duration of manufacture are the quantitative parameters which can be assessed with increasing confidence as the technology development progresses, contributing to overall Affordability of the technology.

3.9 AFFORDABILITY

3.9.1 DEFINITION

The scope of this document includes technology associated with electricity generation from ocean waves and tidal streams. Therefore:

Evaluation of Affordability relates to the cost of electricity generated from the wave or tidal stream resource, relative to the market rate for electricity.

LCOE is generally measured using the parameter of Levelised Cost of Energy (LCOE), which is a project-level parameter, quantifying the cost of electricity into the market and therefore including the costs of the whole system.

The evaluation of LCOE requires extensive input data, which is often difficult to obtain at early stages of technology (or indeed project) development, where knowledge of cost and performance is sparse and of a low confidence-level.

A commonly applied technique to ease these problems is to use an LCOE calculation tool that complements the best available project data with typical values from wider sector experience (see 3.9.4 for further detail on this method).

Sabela D10 turbine at Fromveur Passage, France
Courtesy: SABELLA

3.9.2 EVALUATION CRITERIA

Evaluation Criteria	Units	Format
CAPEX (Capital Expenditure), integrating costs associated with: • Manufacturability • Installability • Financing	£, € or $	Numerical value
OPEX (Operational Expenditure), integrating costs associated with: • Maintainability • Installability (following any off-site maintenance)	£, € or $ per annum	Numerical value
LCOE (Levelised Cost of Energy)	£, € or $ per MWh	Numerical value LCOE provides a comparator against the market rate for electricity and other generation technologies, defined as: $LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}}$ Where: AEP_t = Annual electricity production in year t R = Discount rate N = Economic life of the system

Table 24 Evaluation Criteria for Affordability (wave and tidal stream)

CAPEX and OPEX are applicable at all levels of aggregation while LCOE is a project-level parameter. An estimate of LCOE can be calculated for subsystems by fulfilling the remaining input parameters with typical values from wider sector experience as indicated in section 3.9.4.

Affordability represents the key Evaluation Area in the scope of this document, with all other Evaluation Areas acting as inputs to it (see section 2.3).

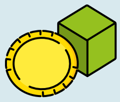
3.9.3 STAGE ACTIVITIES

Stage	Stage Activities
Stage 0 Concept creation	• Definition of technology and market requirements and challenges associated with Affordability (the problem statement) • Selection of high-level Affordability targets appropriate to the technology • Basic estimates of CAPEX based on fundamental relationships between physical and economic parameters (e.g. material cost) and cost of similar technologies (e.g. PTO or other subsystem) • Use of typical project and technology-level cost breakdowns from wider sector experience to extrapolate costs for unknown system elements
Stage 1 Concept development	• High-level CAPEX evaluation of key components of the commercial-scale technology • Development of an initial concept subsystem cost breakdown • Use of typical system and project cost breakdowns from wider sector experience to complete cost evaluation (see section 3.9.4 for a supporting method) • Integration of high-level CAPEX and OPEX evaluations with energy yield calculated by appropriate numerical models to calculate LCOE in a proposed commercial site

Stage 2
Design optimisation
	• Development of a Levelised Cost of Energy (LCOE) model integrating:
	• initial CAPEX of key components of the commercial-scale technology under development
	  • typical system and project cost breakdowns from wider sector experience to provide cost evaluation of other systems or subsystems (see section 3.9.4 for a supporting method)
	  • O&M model and FMEA to evaluate OPEX and availability
	  • Energy yield evaluated using appropriate numerical models
	• Application of suitable learning rates and economies-of-scale to evaluate LCOE for:
	  • the first-of-a-kind commercial-scale prototype (Stage 4)
	  • a “mature sector” technology (e.g. a 10MW array at 1GW global installed capacity)

Stage 3
Scaled demonstration
	• With further knowledge gained from wider stage 3 activities, development of a Levelised Cost of Energy (LCOE) model integrating:
	  • detailed CAPEX of key components of the commercial-scale technology under development
	  • typical system and project cost breakdowns from wider sector experience to provide cost evaluation of other systems or subsystems (see section 3.9.4 for a supporting method)
	  • Further developed O&M model and FMEA to evaluate OPEX and availability
	  • Energy yield evaluated using appropriate validated numerical models
	• With further knowledge gained from wider stage 3 activities, application of suitable learning rates and economies-of-scale to evaluate LCOE for:
	  • the first-of-a-kind commercial-scale prototype (Stage 4)
	  • a “mature sector” technology in a 10MW array at 1GW global installed capacity

Stage	Stage Activities


Stage 4
Commercial-scale single device demonstration
	• Completion of a system-breakdown for the commercial-scale technology including all systems and subsystems
	• Finalisation of a Levelised Cost of Energy (LCOE) model integrating:
	  • Detailed costing of the as-built commercial scale device to evaluate CAPEX
	  • Refined O&M, FMEA, power capture and conversion modelling to evaluate OPEX, availability and energy yield
	  • Evaluation of array infrastructure, balance of plant, learning rates, operational and finance costs
	• Application of suitable learning rates and economies-of-scale to evaluate LCOE for a “mature sector” technology in a 10MW array at 1GW global installed capacity

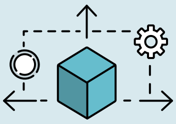

Stage 5
Commercial-scale array demonstration
	• Finalisation of system-breakdown for optimised commercial-scale technology including all systems, subsystems and array infrastructure
	• Finalisation of a Levelised Cost of Energy (LCOE) model integrating
	  • Detailed costing of the as-built commercial-scale array system-breakdown to evaluate CAPEX
	  • Refined O&M, FMEA, power capture and conversion modelling to evaluate OPEX, availability and energy yield
	• Application of suitable learning rates and economies-of-scale to evaluate LCOE for a “mature sector” technology in a 10MW array at 1GW global installed capacity

Table 25 Stage Activities supporting characterisation and evaluation of Affordability (wave and tidal stream)

Orbital Marine Power
Courtesy: Orbital Marine Power

3.9.4 LCOE EVALUATION OF INCOMPLETE SYSTEMS

Evaluation of LCOE at early stages of technology development, or when developing a subsystem (rather than a whole system or project), can be challenging due to lack of input data for the calculation. This section provides some guidance to assist conversations between investors and technology developers at early stages of development. Partial design consensus has been achieved in the tidal stream technology development. This has not occurred in wave energy technology, with a much larger number and variety of wave energy devices and associated subsystems at various stage of development. Due to this difference in sector maturity, this additional guidance is only considered necessary for wave energy technology development, however, it could be easily adapted.

A simple LCOE calculation tool (20) can support early stage LCOE evaluation, using the best available data from the project and typical data from wider sector experience where project specific data is not available.It is important to note that the LCOE calculated using such a tool is not highly accurate however, it does provide a framework within which Affordability can be evaluated at early to mid-stages of development.

It provides:

- Calculation of a baseline LCOE from which the Affordability impact of individual innovations (e.g. subsystems) can be evaluated
- An opportunity to explain how the characteristics of an innovative technology *challenge* or *modify* the typical values or assumptions, leading to further critical evaluation of the technology's Affordability credentials

A breakdown of the proportions of the cost centres in a typical wave energy project is shown in Figure 12.

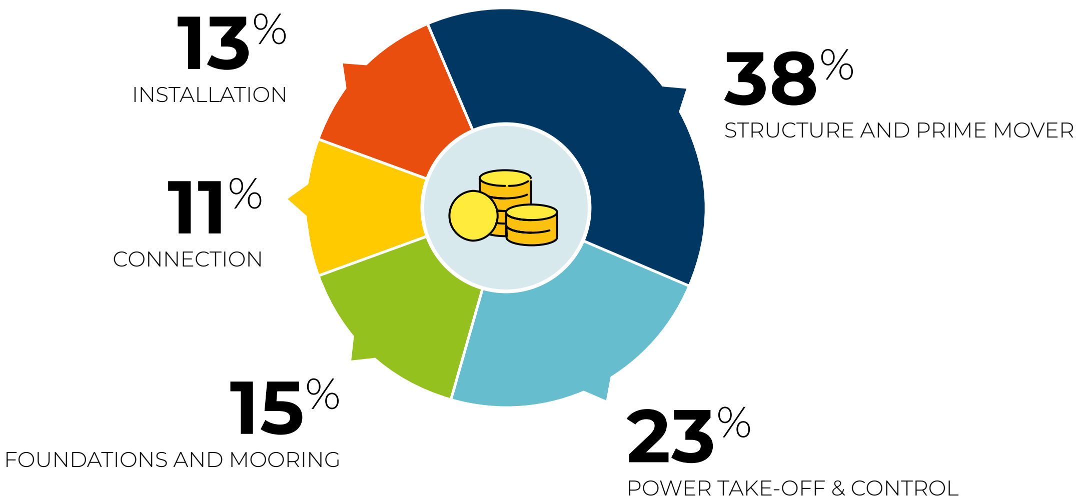


Figure 12 Breakdown of cost centres in a typical wave energy project (21)

This breakdown can be useful to put a subsystem in the context of a complete project in situations where a developer of a subsystem only has data for their own technology. To evaluate its potential impact on the project-level cost of energy, a CAPEX value for that subsystem can be entered and the typical cost breakdown for the remainder of the inputs used. This combination of known and typical costs can be completed in numerous ways, for example:

1. Maintain the typical cost breakdown – scale all typical CAPEX or project cost inputs to maintain the same percentage split.
2. Maintain the typical absolute costs – keep typical CAPEX or project cost values constant for a particular target or expected LCOE.
3. Combination of the options 1 & 2 along with other justifiable adjustments, for example an inflatable structure could require the same PTO CAPEX as a rigid structure but justify a significant reduction in installation costs.

Where full detailed costs are not available for all elements of a project, including availability, finance costs or O&M schedules, other approaches must be taken. During early stage technology development, LCOE calculations for a project will not be accurate, but can provide enough information to inform decisions on a comparative basis. With all other costs being equal, what is the impact on LCOE of a design decision within the technology? Such information can act as a baseline for comparing against other information available from the wider sector.

3.10 ENVIRONMENTAL ACCEPTABILITY

3.10.1 DEFINITION

Environmental acceptability can be defined as the ability to make effective use of natural resources, reduce the risks and harms to the operating environment, comply with the relevant regulations, and generate induced benefits whenever possible.

Considerations within this Evaluation Area should cover the full lifecycle, and all potentially impacted environments. It is also important to note that acceptability is not just a retrospective evaluation process; forward-facing decisions that influence a technology's future Environmental Acceptability start at the requirements capture and concept design stage, and it should be actively considered as a driver from the beginning.

3.10.2 STAGE ACTIVITIES

Activities related to Environmental Acceptability are numerous, varied and differ greatly according to many factors, including:

Factors	Stage Activity examples
Technology characteristics	Design and operational consideration of how such characteristics interact with the environment.
Supply chain	Use of biologically inert materials and solvents for components; analysis of the carbon emission of manufacturing processes
Geographic, oceanographic, and ecological location and characteristics	Assessment of species and habitats potentially at risk; study of baseline conditions and implications of introducing technology
Applicable regulatory and consenting regime	Early discussions of technology and operational characteristics and their compatibility with regulations

Delivery of Environmentally Acceptable ocean energy technologies is driven and managed at various levels from specific evaluation of impacts and implications of activity in the environment up to the legal processes, such as consenting, permitting and licensing, required in the relevant jurisdiction.

The intent of this section is to present the perspective of a funder of wave and tidal technology development, to consider the importance of Environmental Acceptability as a technology characteristic, and to signpost the key activities and processes used in its evaluation and management. While the detailed activities are influenced by technology type, geography, marine species and habitats that may be at risk, and legislation, the guidance and evaluation of the environmental credentials are delivered by two key processes: Lifecycle Analysis (LCA) and Environmental Impact Assessment (EIA).

LIFECYCLE ANALYSIS (LCA)

At its broadest, in terms of project duration and environmental scope, the sustainability credentials of a technology and its exploitation should be considered through a Lifecycle Assessment (LCA). Being able to intimately understand and quantify the environmental impacts of a technology or product, including its material and energy inputs, over a defined duration and across a range of impact categories is key to establishing a truly transparent account of its overall environmental impact. The LCA is therefore a useful tool to evaluate a given technology in the contexts of the circular economy, sustainability and socio-economic considerations.

While wave and tidal devices can be considered emission-free technologies as they generate electricity, their journey from inception to deployment and to eventual decommissioning will contain a level of unavoidable environmental impacts. Therefore, it is important that any device deployment be viewed holistically across its entire lifetime to ascertain whether its environmental impact is outweighed by its energy generation.

With a range of materials, a diverse supply chain and a wide geographic spread of potential deployment sites, accounting for the different variables that mark the lifetime of a device is a challenging task. Establishing a clear set of life cycle phases is an important first step in the construction of an LCA, allowing a range of factors to be included or omitted as required:

From this point, system boundaries can be drawn which allow for these phases to be accurately tracked, and discounted from the LCA, if required. The scope of an LCA can be defined by one of three system boundaries:

1. Cradle-to-gate (phases 1 & 2) considers the overall environmental impact of a product from the point of raw material extraction to the point it leaves the factory 'gate'.
2. Cradle-to-grave (phases 1 – 5) considers the entire process, from the point of raw material extraction to its end-of-life state, giving an accurate representation of the environmental impact of a given device over its entire lifetime.
3. Cradle-to-cradle (phases 1 – 5 – 1) introduces the principles of the circular economy into LCA processes, and accounts for the materials at the end-of-life state, being recycled or repurposed in the next iteration of a product or technology.

The range of inputs required to create an accurate LCA means that the outcome cannot be quantified by one number, but rather is represented by a range of impact category groups that include but are not limited to: climate change (kg CO_2-eq); embodied energy (MJ); and marine eutrophication (Kg N-eq). One of the primary challenges facing the sector is expanding the focus of LCAs beyond the groups listed above, expanding our existing knowledge relating to potential trade-offs or co-benefits across a broad range of environmental impacts.

While the wave and tidal sectors do not currently benefit from the same body of empirical analysis as more mature renewable energy technologies such as wind and solar, future deployment estimates merit concerted efforts to bridge this gap and ensure that the sector as a whole continues to progress and evolve in a sustainable manner. Areas of potential interest lie in the design of composite materials with high recyclability rates, increased component durability and lower transportation weights, a reduction of fossil fuels in the overall supply chain and decreasing the requirements for sea vessel operation during installation, maintenance and decommissioning.

ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

Focusing on the marine environment and the in-sea phases of a project, the acceptability of a technology and deployment is considered through an Environmental Impact Assessment (EIA) and accompanying processes, driven by legislation and regulation, and based around evaluation of risks, benefits and harms.

Marine energy development cannot progress unless the devices, anchors and foundations, mooring lines, power export cables, and other infrastructure are deemed to not cause significant harm to the marine environment, marine animals and habitats, or large-scale ecosystem and oceanographic processes. Determining the level of interaction between marine energy systems and the marine environment has proved challenging as few systems have been deployed and monitored extensively, and stakeholders, alongside the regulatory community are slow to accept potential risks that might be associated with accelerated deployments.

An assessment of environmental acceptability could be used to measure the level of potential effects of marine energy systems, but such a system has been hindered by several factors:

- Little is known about interactions of marine energy devices and systems as there are few appropriate analogues in the marine environment for some interactions.
- Potential effects are certain to vary broadly based on species of concern and their regulatory status, and on the geographic and oceanographic site conditions where marine energy might be harvested, resulting in little generalized understanding of effects.
- The wide variety of marine energy device types and configurations make it difficult to generalize how tidal or wave devices might affect key environmental components.
- Acceptance of environmental risk is dictated by regulatory structures and laws that differ from country to country and region to region, often steeped in rationales that are not directly applicable to marine energy system interactions.

Interactions between marine energy systems and the marine environment that drive the environmental acceptability of marine energy project can be described as stressors and receptors. Stressors are the part of a marine energy system or device that may cause harm or stress to the marine environment. These stressors vary by technology, duration of deployment or interaction, site characteristics, and geographic location. Receptors are marine animals living in the area of a marine energy system, habitats where devices are deployed, and oceanographic and ecosystem processes. Seven key stressor-receptor interactions for wave and tidal energy devices have been defined by OES-Environmental (Copping et al. 2020):

1. **Collision risk** between moving parts of a marine energy device (blades of tidal turbine) and marine animals
    - Animals of concern: fish, marine mammals, diving seabirds and potentially sea turtles
2. **Underwater noise** emitted from operational marine energy devices (rotation of turbine blades, movements of a floating device, mooring lines, and cables)
    - Animals of concern: marine mammals, fish, sea turtles, and invertebrates
3. **Changes in benthic** (seafloor) **and pelagic** (water column) **habitat** associated with the presence of marine energy systems
    - Animals of concern: macro and micro-benthic invertebrates and demersal fish, pelagic organisms including fish, sea turtles, marine mammals, and invertebrates

4. **Electromagnetic fields** associated with power export cables
   - Animals of concern: certain species of elasmobranchs, crustaceans, fish, and sea turtles
5. **Entanglement** risk of marine animals with mooring lines and underwater cables
   - Animals of concern: marine mammals, large fish, sea turtles
6. **Changes in oceanographic systems** (current speeds, wave heights, water circulation) associated with the presence of marine energy devices
   - Processes of concern: tidal circulation particularly in bays and estuaries, wave heights and shoreline erosion, sediment transport patterns and ecosystem processes including the marine food web
7. **Displacement** of animals due to the presence and operation of marine energy devices in the pelagic or benthic zones
   - Animals of concern: large animals including migratory marine mammals, some fish, sea turtles, also mobile benthic invertebrates

Some of the stressors may not be relevant for small scale developments (one to four devices) but will become important as the industry moves to larger arrays.

OES-Environmental[10], an OES task led by the U.S. with the Pacific Northwest National Laboratory (PNNL), is an international collaborative project amongst member nations of the International Energy Agency's Ocean Energy Systems (OES) collaborative which synthesizes information and scientific research about MRE and the environment on a global scale into collaborative reports and documents. Additionally, OES-Environmental hosts workshops and webinars to bring researchers together around environmental effects research and supports environmental effects tracks at international conferences.

OES-Environmental is an internationally accepted centre of knowledge for environmental acceptability of marine energy activity. Additionally, the U.S. Department of Energy partnered with the International Energy Agency's Ocean Energy Systems (IEA OES) initiative to create Tethys[11], a database and knowledge management system which hosts OES-Environmental and provides access to information and research about the potential environmental effects of offshore wind and marine renewable energy development.

3.10.3 ENVIRONMENTAL ACCEPTABILITY AS A DESIGN DRIVER

Ideally, a series of wave and tidal technology-specific Evaluation Criteria would be developed that assess the magnitude and likelihood of the potential harms, benefits and risks of a particular marine energy device, system, or array. The data are not yet available to make this happen; however, for certain characteristics (e.g. environmental stressor-receptor interactions), likely outcomes can be inferred. With growing numbers of future deployments featuring strong environmental monitoring programs, such criteria could become more accessible. Knowledge of these characteristics and their potential environmental implications can be used as valuable design drivers, allowing Environmental Acceptability to influence decision making, even at technology concept design stage (Stage 0). Such a focus on Environmental Acceptability would serve to minimise risks and harms before they are realised, while maximising potential benefits, actively pushing outcomes towards the definition presented above. The sector is developing various tools to support the consideration of Environmental Acceptability in the design process, an example being the Environmental and Social Acceptability tool included with the DTOceanPlus[12] software suite.

10 https://www.ocean-energy-systems.org/oes-projects/assessment-of-environmental-effects-and-monitoring-efforts-for-ocean-wave-tidal-and-current-energy-systems/
11 https://tethys.pnnl.gov/about-oes-environmental
12 https://www.france-energies-marines.org/en/projects/dtoceanplus/ This project received funding from the European Research and Innovation Programme Horizon 2020

3.11
ALIGNMENT OF GUIDANCE WITH IEC

As discussed in section 1.7, this Framework helps funders select the most promising technologies by agreeing *what* development activities and key evaluation parameters they should expect from developers. In partnership, IEC Technical Specifications help developers advance their technologies correctly by detailing *how* activities and evaluations are carried out.

In fact there is strong alignment between the Evaluation Areas, presented here, and the growing body of IEC Technical Specifications, with a common understanding of the technical characteristics the sector identifies as necessary for a successful technology.

Table 26 presents a summary of the alignment, effectively linking the interests of funders and investors with the technology developers' need for detailed guidance on how to successfully deliver their development work.

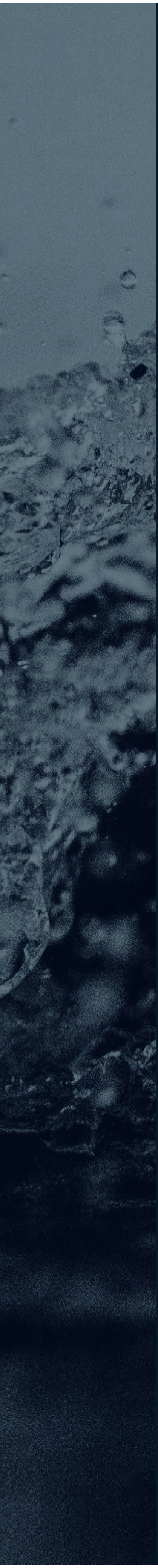
Zhoushan Sharp Eagle
Courtesy: GIEC

IEC Document		Relevant IEA-OES Stages						Relevant IEA-OES Evaluation Area									
Number	Short name	0	1	2	3	4	5	Power Capture	Power Conversion	Controllability	Reliability	Survivability	Maintainability	Installability	Manufacturability	Affordability	Environmental Acceptability
62600-1:2020	Vocabulary (IEV Part 417)	X	X	X	X	X	X	X	X		X	X	X				
62600-2:2019	Design	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
62600-3:2020	Loads					X	X	X	X	X	X	X			X		
62600-4:2020	Technology Qualification	X	X	X	X			X	X	X	X	X	X	X	X	X	
62600-10:2021	Moorings	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
62600-20:2019	OTEC Design	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
62600-30:2018	Power Quality					X	X	X	X								
62600-40:2019	Acoustics					X	X										X
62600-100:2012/ COR1:2017	Wave Power Performance					X	X	X	X								
62600-101:2015	Wave Resource Assessment	X	X	X	X	X	X										X
62600-103:2018	Wave Scale-testing	X	X	X	X			X	X	X	X	X	X	X	X	X	X
62600-200:2013	Tidal Power Performance					X	X	X	X								
62600-201:2015	Tidal Resource Assessment	X	X	X	X	X	X										X
62600-202:2022	Tidal Scale-testing		X	X	X			X	X	X	X	X	X	X	X	X	
62600-300:2019	River Power Performance					X	X	X	X								
62600-301:2019	River Resource Assessment	X	X	X	X	X	X										X

Table 26 Alignment of IEC Technical Specifications with IEA-OES Evaluation Areas

This diagram will be updated in future editions to reflect the growing body of guidance being produced by IEC TC-114. These additions will ensure that the expectations of *what* activities and evaluation parameters should be delivered by developers (IEA-OES) are supported by standards detailing *how* to deliver those activities and evaluations (IEC). This completeness will allow developers, Certification Bodies and Test Laboratories (ISO/IEC) and Conformity Assessment (IECRE) to fully support the needs of technology customers, from public funders through the private investors. This section is focused on IEC guidance, but it should be noted that additional technical guidance is provided by the ITTC[13].

13 https://ittc.info/



ANNEX A
PRECEDING ACTIVITY

The following workshops and collaboration activities have provided input to this document, including sector-wide stakeholder engagement.

Workshop on Metrics Used for Measuring Success of Wave Energy Converters

This workshop was attended by 52 key stakeholders from 10 countries and 37 different organisations, covering a broad range of competencies including technology development, supply chain, research, policy making, test facilities and technical verification. It was held in Edinburgh following ICOE on February 26th 2016.

The main objectives for the workshop were to review and agree on a list of capabilities and functional requirements for a Wave Energy Converter (WEC) and to identify and agree a set of suitable metrics to support a list of WEC requirements.

The themes identified in the workshop (26) formed valuable input to the on-going international effort which continued into subsequent workshops.

Workshop on Stage Gate Metrics for Ocean Energy Technology Development

This event was attended by 43 key stakeholders from 10 countries and 32 different companies, covering a broad range of competencies including technology development, supply chain, research, policy making, test facilities and technical verification. It was held in Edinburgh on 16th September 2016. The workshop report (22) presents the process and outputs from a workshop held to identify and agree a set of metrics and associated success thresholds, which can support stage-gated development programmes for Ocean Energy technologies. This workshop was part of a network of international collaboration activity, instigated by the International Energy Agency Ocean Energy Systems group, which intended to bring together and build upon metric definition activity in stage-gated technology development programmes in the USA (Department of Energy), UK (Wave Energy Scotland) and Ireland (WestWave).

Ocean Energy Stage Gate Metrics Validation Workshop

This event was attended by 38 stakeholders from the wave and tidal energy sector and was held in Edinburgh on 29th November 2017. Stakeholder groups represented were public funders, technology developers, academia, government bodies and test sites from eight different countries. The workshop report (10) summarises the content which was presented during the workshop and incorporates the feedback received from the range of stakeholders in attendance. The report presents a set of stage gate metrics for ocean energy technology development.

4

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